An fMRI study of scientists with a Ph.D. in physics confronted with naive ideas in science

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A central challenge in developing conceptual understanding in science is overcoming naive ideas that contradict the content of science curricula. Neuroimaging studies reveal that high school and university students activate frontal brain areas associated with inhibitory control to overcome naive ideas in science, probably because they persist despite scientific training. However, no neuroimaging study has yet explored how persistent naive ideas in science are. Here, we report brain activations of 25 scientists with a Ph.D. in physics assessing the scientific value of naive ideas in science. Results show that scientists are slower and have lower accuracy when judging the scientific value of naive ideas compared to matched control ideas. fMRI data reveals that a network of frontal brain regions is more activated when judging naive ideas. Results suggest that naive ideas are likely to persist, even after completing a Ph.D. Advanced experts may still rely on high order executive functions like inhibitory control to overcome naive ideas when the context requires it.

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INTRODUCTION

Over the course of their lives, humans hold to many naive ideas or misconceptions about how nature works. Contrary to what one might have thought, these naive ideas are often far from being irrational or senseless and can even be useful in everyday living. However, some naive ideas have proved to be a “pain in the neck” for science educators, since they are often incompatible with the content of science curricula. They are also sometimes very resistant to change. It is, for instance, naively and widely believed that summer is the warmest season because the Earth is the closest to the Sun. This naive idea that warmer means closer is quite useful in day-to-day life and is probably reinforced by common hands-on experiences, such as approaching a hand from the stovetop or a campfire and getting a warmer sensation. Hence, when teaching seasons on Earth, educators can be confronted with a prevailing naive idea that competes with the scientific reason according to which seasons are the result of the Sun’s apparent motion, which results in changes in the intensity of the Sun’s rays and changes in the length of day.

One important goal of science education is therefore to encourage the conceptual change process, a learning pathway from naive or pre-instructional ideas to the scientific ideas. However, conceptual change is often very hard to accomplish, and students frequently revert to naive ideas despite carefully planned teaching. Recent contributions to conceptual change literature highlight the difficulty to cope with the coexistence of naive and scientific ideas within an individual’s mind. Naive ideas more than scientific ones rely on fast and effective cognitive resources that are deeply anchored in human intuitions or heuristics and reinforced in real-life contexts. Indeed, behavioral studies show a tendency to endorse naive ideas in speeded response conditions and observe increased response time to process problems that trigger naive ideas of science. Altogether, these findings are interpreted as evidence of an increased demand on executive control to allow resistance to distractors and interferences. Hence, conceptual change is thought to be contingent upon the capacity to suppress or inhibit dominant naive ideas to allow the expression of less prevalent scientific ones.

Behavioral studies explored the processing of naive ideas in experts with statement-verification tasks. Results suggest that mature scientific knowledge doesn’t involve radically overwriting or erasing naive ideas. Experts in biology exhibit a confusion similar to the one of children when confronted with the naive ideas of cows having udders in order to milk them. Instead of its extended education, professional scientists are as accurate as younger adults at verifying statements related to naive ideas, but the lag in response times between naive and matched control statements is larger than for younger adults. Similar findings are observed with other scientific reasoning tasks. Physicists and chemists still hold many naive ideas about thermal phenomena generally believed by middle school students. Both physicists, whose knowledge is in accord with Newtonian principles, and novices exhibit the same common naive idea related to impetus, i.e., that continuation of motion depends on continued action of a force.

Over the past two decades, exploration of the neural substrate of scientific expertise has shed additional light on the difficulty, even for experts, to cope with the coexistence of naive and scientific ideas. Most studies have examined experts and highly competent individuals to understand the transition from naive to scientific ideas as experts are believed to have achieved conceptual change. The comparison of brain activation patterns between experts and novices point to a correlation between expertise and increased activity in key brain areas of inhibitory control, including the bilateral inferior frontal gyrus (IFG) and middle frontal gyrus (MFG) to a certain extent the anterior cingulate cortex (ACC). ACC's contribution to effortful control.
compared brain activation patterns between physics undergraduates (at least five college courses) to arts and humanities undergraduates (no high school or college physics courses), when evaluating simple electric circuits diagrams to expose the “single-wire” naive idea and found increased activity in the IFG, MFG, ACC, as well as in the angular gyrus for physics undergraduates. Using a similar approach, Brault Foisy et al. showed that undergraduate physics students successfully assessing the correctness of movies with free-falling bodies (which trigger the “heavier objects fall faster” naive idea) recruited more significantly the prefrontal brain network comprising the IFG and MFG compared to humanities students who can’t overcome their naive ideas about free fall. Allaire-Duquette et al. findings suggest stronger recruitment of the IFG and the MFG in more competent high school students confronted with naive ideas across a wide range of scientific domains. Ultimately, results of all these studies show that the IFG, the MFG and the ACC were significantly more activated in more competent individuals. These findings support the hypothesis of a relation between conceptual change and inhibitory control, i.e., the suppression of prepotent ideas or thoughts to protect working memory’s mental workspace. One possible explanation is that even in experts, naive ideas have not been erased or replaced after learning scientific ideas; they are still encoded in neural circuits that must be inhibited to provide scientifically appropriate responses. However, no neuroimaging study has yet explored how persistent these naive ideas are since the experts examined so far are at most undergraduates. What happens to naive ideas in the brain of scientists with a Ph.D. who have gone through extensive scientific training remains to be explored.

In the present study, we go one step further by examining how naive ideas are processed by scientists with a Ph.D. in physics. We measured brain activity associated with judging the scientific value of statements related to naive ideas in their domain of expertise (physics), or a domain in which they have a more basic level of expertise (biology). We used an experimental task featuring incongruent statements intended to trigger a commonly held naive idea of a given natural phenomenon that leads to a scientifically inappropriate judgement. We also used matched congruent statements triggering the same naive idea, but in a scenario where there is no discrepancy between the naive and scientific ideas therefore the naive idea leads to a scientifically appropriate judgement. Based on previous studies, we hypothesize that evaluating incongruent statements in physics and biology will be associated with increased activity in brain regions including IFG, MFG, and ACC, while acknowledging that functional specificity related to each domain could vary. Indeed, previous findings with undergraduates suggest that inferior and middle prefrontal brain areas, as well as ACC should be more strongly recruited when scientists with a Ph.D. in physics are confronted with naive ideas (incongruent statements) in biology compared to physics, since no advanced training has targeted them and therefore naive ideas are probably still prevailing strongly.

Undoubtedly, physicists have been repeatedly exposed to a large number of problems and scientific ideas in physics; therefore, they have less relative exposure to naive ideas as compared to scientific ideas in physics than in biology. On the one hand, this could cause naive ideas in physics to prevail less in physicists. It could also be argued that greater expertise in physics will be related to more efficient inhibition of naive ideas rather than the naive idea being less prevalent. This prediction would be compatible with studies showing that the inhibition of a prepotent response might become easier with age and increased competency. A third alternative explanation could be that the scientific ideas become more prevalent or that physicists even develop a scientific intuition, as suggested by De Neys or Bago and De Neys. All of three proposed explanations support the prediction that key inhibitory control brain areas (IFG, MFG, and ACC) might potentially be less recruited, when confronted with naive ideas in physics compared to biology. However, it should be noted that our findings don’t allow to test for the different account of these alternative explanations, and that future work could address this finer grain exploration of the relation between expertise and processing of naive ideas.

RESULTS

Behavioral data

As expected, physicists are more accurate in assessing physics statements than biology statements (t(24) = 4.360, p < 0.001, d = 0.5 (d = (M1 – M2)/Sp, where M1 and M2 denote the sample means for groups 1 and 2, and Sp denotes the pooled estimated population standard deviation), CI 95% [-8.0, -2.9]; Δphysics = 88.4 ± 11.4% [mean ± standard deviation]; Δbiology = 83.0 ± 9.0%) although the difference is small (5.4%; Fig. 1b). In physics and biology, participants were more accurate at verifying the scientific value of the congruent statements relative to incongruent ones (Fig. 1b).

(PHYSICS: t(24) = 8.522, p < 0.001, d = 1.7, CI 95% [11.8, 19.4]; Δcongruent = 96.3 ± 4.9%; Δincongruent = 80.6 ± 10.6%. Biology: t(24) = 8.888, p < 0.001, d = 1.5, CI 95% [10.2, 16.3]; Δcongruent = 89.6 ± 4.9%; Δincongruent = 76.4 ± 7.1%; chance = 50%). Verifying the scientific value of the congruent statements relative to incongruent ones was also faster in both areas of expertise (Fig. 1c). (PHYSICS: t(24) = 10.988, p < 0.001, d = 2.1, CI 95% [-759.1, -519.0]; Δcongruent = 3542 ± 754 ms; Δincongruent = 4181 ± 811 ms. Biology: t(24) = 4.830, p < 0.001, d = 0.9, CI 95% [-389.1, -156.2]; Δcongruent = 3182 ± 699 ms; Δincongruent = 3455 ± 749 ms). In physics, response time increased twice as much as in biology between congruent and incongruent statements (Δphysics = +639 ms or 18%; Δbiology = +273 ms or 9%).

Congruency-dependent modulation of BOLD signal

We first explored cortical sites where brain responses are modulated by congruency, when expertise is averaged across levels and consequently, which activations are higher for incongruent statements compared to congruent statements or conversely. The results show different brain activation patterns of scientists judging the scientific value of incongruent statements compared to congruent statements (Table 1 and Fig. 2). The analysis identified a set of areas in the left IFG, bilateral superior frontal gyrus, and bilateral ACC. Higher blood oxygen level dependent (BOLD) response in all three clusters was found for incongruent statements compared to congruent statements. Additional areas are identified by t-contrasts and reveal that incongruent statements, more than congruent ones, activated also the bilateral cerebellum and the MFG, while conversely the congruent statements activated the bilateral middle occipital gyrus more than incongruent ones.

“Expertise x congruency”-dependent modulation of BOLD signal

We then searched for differences in activation profiles for the congruent and incongruent statements, depending on the area of expertise (i.e., physics and biology). This interaction effect identified a cluster in the bilateral dorsal ACC (Table 2 and Fig. 3). Then, we assessed the direction of the interaction effect. We examined which regions were more activated by incongruent or congruent statements for biology and physics independently. In physics (Table 3 and Fig. 4), areas more activated for incongruent than congruent statements include left supplementary motor area, left middle occipital gyrus, left superior frontal gyrus, bilateral MFG, and left IFG. The right middle occipital gyrus is the only area more activated for congruent than incongruent statements. The changes in BOLD signal for each area are presented in Fig. 5.
In regard to statements in biology (Table 4 and Fig. 6), areas more activated for incongruent than congruent statements include left IFG, bilateral ACC, bilateral caudate, right insular cortex, bilateral superior frontal gyrus, and right midcingulate gyrus. Areas more activated for congruent than incongruent statements are comprised of the bilateral middle occipital gyrus and left precentral gyrus. T-contrasts reveal that the interaction effect is attributed to the activation pattern of processing of incongruent statements in biology for which the participants possess basic expertise. The changes in BOLD signal for each area are presented in Fig. 7.

**DISCUSSION**

In this functional magnetic resonance image (fMRI) study, congruent and incongruent statements about natural phenomena were presented to scientists with a Ph.D. in physics. Each incongruent statement relates to a naive idea that interferes with

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**Table 1.** Significant activation clusters for the main effect CONGRUENCY and the subsequent t-contrasts between congruent and incongruent statements.

| Brain areas                      | MNI peak coordinate | Main effect of CONGRUENCY | Incongruent > congruent | Congruent > incongruent |
|----------------------------------|---------------------|---------------------------|-------------------------|------------------------|
|                                  | x      y   z | k | F   p | k | t   p | k | t   p |
| Frontal lobe                     |         |               |                         |                        |
| L Inferior frontal gyrus (orbital), R Superior frontal gyrus (orbital), bilateral anterior cingulate gyrus | −21 24 | −9 245 27.34 | 0.002 | 118 4.90 <0.001 | — | — | n. s. |
| Bilateral superior frontal gyrus (medial) | 0 27 51 | 259 214.94 | 0.0001 | 180 4.46 <0.0001 | — | — | n. s. |
| L Middle frontal gyrus           | −51 15 42 | — | — | n. s. | 49 3.75 <0.0001 | — | — | n. s. |
| Occipital lobe                   |         |               |                         |                        |
| R Middle occipital gyrus         | 39 −84 9 | — | — | n. s. | — | — | n. s. | 175 4.63 <0.0001 |
| L Middle occipital gyrus         | −30 −96 18 | — | — | n. s. | — | — | n. s. | 49 3.62 0.001 |
| Hindbrain                        |         |               |                         |                        |
| R Cerebellum crus I              | 33 −66 −33 | — | — | n. s. | 39 4.03 <0.0001 | — | — | n. s. |
| R Cerebellum crus II             | 6 −84 −24 | — | — | n. s. | 33 3.70 <0.0001 | — | — | n. s. |

Note: coordinates are reported in MNI space as given by SPM8, main effect at $p_{FWE-CORRECTED} < 0.05$ and t-contrasts at $p_{UNCORRECTED} < 0.005$, expected voxels per cluster $k = 11$ for main effect and $k = 14$ for t-contrasts, second-level analysis (random effect analysis, full factorial, and t tests). Coordinates are reported in MNI space as given by SPM8. Anatomical labels are based on the AAL (automated anatomical labeling) atlas (Tzourio-Mazoyer et al., 2002). The first label represents the location of the peak activation, additional labels denote submaxima if located in a different brain region.

L left, R right.

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**Fig. 1** Behavioral results. a On each trial, participants were presented with a written statement and judged it as scientifically correct or incorrect. b Performance in this task (% correct). c Mean response time in this task (ms). Center line represents median; box limits, upper and lower box limits represent quartile 1 and quartile 3; whiskers represent minimum and maximum values; * represents potential outliers ± 1.5× IQR (interquartile range). * $p < 0.001$. 

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In regard to statements in biology (Table 4 and Fig. 6), areas more activated for incongruent than congruent statements include left IFG, bilateral ACC, bilateral caudate, right insular cortex, bilateral superior frontal gyrus, and right midcingulate gyrus. Areas more activated for congruent than incongruent statements are comprised of the bilateral middle occipital gyrus and left precentral gyrus. T-contrasts reveal that the interaction effect is attributed to the activation pattern of processing of incongruent statements in biology for which the participants possess basic expertise. The changes in BOLD signal for each area are presented in Fig. 7.

**DISCUSSION**

In this functional magnetic resonance image (fMRI) study, congruent and incongruent statements about natural phenomena were presented to scientists with a Ph.D. in physics. Each incongruent statement relates to a naive idea that interferes with
a scientifically appropriate judgment, while otherwise equivalent congruent statements triggered the same naive idea, but in a scenario where there is no discrepancy between the naive and scientific ideas. We searched for greater activations to incongruent than to congruent statements to investigate what happens in experts’ mind when confronted with commonly held naive ideas that interfere with a scientifically valid judgment they have been

**Table 2.** Significant activation cluster for the interaction effect between EXPERTISE and CONGRUENCY.

| Brain areas | MNI peak coordinate | EXPERTISE × CONGRUENCY |
|-------------|----------------------|------------------------|
|             | x  y  z  k  F p_{FWE-corr} |
| Frontal lobe |                     |                        |
| Bilateral dorsal anterior cingulate cortex | 6  24  0  190 24.35 0.01 |  |
| Note: coordinates are reported in MNI space as given by SPM8, p_{FWE CLUSTER LEVEL} < 0.05, expected voxels per cluster \( k = 11 \), second-level analysis (random effect analysis, full factorial), MNI coordinates in mm. Anatomical labels are based on the AAL (automated anatomical labeling) atlas (Tzourio-Mazoyer et al., 2002). |

**Table 3.** Activation clusters for \( t \)-contrasts between congruent and incongruent statements in physics.

| Brain areas | MNI peak coordinate | INCONGRUENT > CONGRUENT |
|-------------|----------------------|--------------------------|
|             | x  y  z  k  t  p_{uncorr} |
| Frontal lobe |                     |                          |
| L Supplementary motor area | −3  24  48  158 5.34 <0.0001 |
| L Superior frontal gyrus (dorsolateral) | −21  21  57 169 4.50 <0.0001 |
| R Middle frontal gyrus | 33  21  54 127 4.31 <0.0001 |
| L Inferior frontal gyrus (triangular) | −48  33  21  64 4.27 <0.0001 |
| L Middle frontal gyrus | −42  54  3  55 4.20 <0.0001 |
| Occipital lobe |                     |                          |
| L Middle occipital gyrus | −39 −78 39 153 4.81 <0.0001 |
| CONGRUENT > INCONGRUENT | Occipital lobe | R Middle occipital gyrus | 39 −84 9 63 3.95 <0.0001 |
| Note: coordinates are reported in MNI space as given by SPM8, p_{UNCORRECTED} < 0.005, expected voxels per cluster \( k = 11 \), second-level analysis (random effect analysis, \( t \) tests), MNI coordinates in mm. Anatomical labels are based on the AAL (automated anatomical labeling) atlas (Tzourio-Mazoyer et al., 2002). L left, R right. |
Our hypothesis was twofold. First, activity in IFG, MFG, and ACC will be greater for naive ideas compared to control ones. Naive ideas are thought to be deeply rooted in humans’ cognition and are often reinforced by everyday life experiences. They are often spontaneous, accompanied by a feeling of certainty, and are subject to recency effects. This hypothesis is based on findings suggesting that even advanced undergraduate students in physics may still hold to naive ideas of science encoded in neural networks that must be inhibited in order to answer scientifically. Secondly, we also hypothesized that the activation of inhibitory control is likely more prominent for statements in biology since participants possess a more basic level of expertise in this area compared to physics. Indeed, despite being persistent, the prevalence of naive ideas appears to decrease with age/expertise. Potvin and Cyr found that science teachers’ responses to a buoyancy task are faster and more accurate than preschoolers’, elementary students’, and secondary students’ responses. Lanoë, Vidal, Lubin, Houdé, and Borst observed that experts in mathematics need to inhibit naive ideas when solving arithmetic word problems, but the negative priming effect (effect of prior exposure to naive ideas on subsequent responses) was of smaller amplitude than in nonexperts.

Performance data show that incongruent statements displayed lower accuracy and longer response time than congruent statements, reflecting the interference and performance decrement caused by the contextually irrelevant information of naive ideas. These findings, observed for physics as well as for biology statements, suggest that even with their expertise, physicists’ scientific judgment is still impacted by interfering naive ideas in science. Indeed, when asked to evaluate the scientific value of the statements, participants were more likely to rely on naive ideas of given phenomena, as they are still easily accessible and often reinforced in real-life contexts. This effect has been repeatedly found in studies on interference and inhibitory control mechanisms for different age groups and our results are in line with previous findings demonstrating that participants, including experts, verify statements whose truth value differs from naive ideas (incongruent situations) more slowly and less accurately than statements, where naive ideas do not interfere. Interestingly, as did Shlulman and Legare, we found a larger response lag between congruent and incongruent statements in physics than in biology. However, unlike Shlulman and Legare it is unlikely attributable to our participants being less trained to perform.

### Table 4. Activation clusters for t-contrasts between congruent and incongruent statements in biology.

| Brain areas               | MNI peak coordinate | $p_{\text{uncorr}}$ |
|---------------------------|---------------------|---------------------|
| **Frontal lobe**          |                     |                     |
| L Inferior frontal gyrus  | $-21$ $30$ $-12$ $83$ $4.53$ <0.0001 |
| R Anterior cingulate cortex | $12$ $39$ $24$ $40$ $3.97$ <0.0001 |
| R Insula, R Superior frontal gyrus (orbital) | $27$ $21$ $-15$ $30$ $3.95$ <0.0001 |
| L Anterior cingulate gyrus, R Superior frontal gyrus (medial orbital) | $-15$ $33$ $21$ $105$ $3.86$ <0.0001 |
| R Superior frontal gyrus (medial), R Midcingulate gyrus | $9$ $33$ $39$ $34$ $3.72$ <0.0001 |
| **Occipital lobe**        |                     |                     |
| L Precentral gyrus        | $-48$ $-6$ $42$ $62$ $3.87$ <0.0001 |
| R Middle occipital gyrus  | $33$ $-93$ $12$ $120$ $4.67$ <0.0001 |
| L Middle occipital gyrus  | $-27$ $-96$ $9$ $128$ $4.36$ <0.0001 |

Note: coordinates are reported in MNI space as given by SPM8, $p_{\text{uncorrected}}$ < 0.005, expected voxels per cluster $k=12$, second-level analysis (random effect analysis, t tests), MNI coordinates in mm. Anatomical labels are based on the AAL (automated anatomical labeling) atlas (Tzourio-Mazoyer et al., 2002). The first label represents the location of the peak activation, additional labels denote submaxima if located in a different brain region. L left, R right.
with inhibitory control mechanisms were significantly more activated by incongruent statements. The MFG and IFG, associated with inhibitory control mechanisms, were significantly more activated by incongruent statements. The MFG is generally associated with executive control processes including inhibitory control, working memory, and task switching. This region is found to be particularly active when blocking prepotent responses, as well as reorienting to unexpected stimuli. Neuroimaging studies have also highlighted how the IFG shows increased activation when suppressing prepotent responses and findings suggest that the integrity of left IFG is also critical for the successful implementation of inhibitory control. Moreover, although multiple studies have also associated inhibitory control with the right IFG, the left IFG is more likely activated by semantic inhibitory control, which concurs with the verbal nature of the misconception-oriented task used in our study.

These findings are in line with our hypothesis and provide evidence that even experts with a Ph.D. would need to suppress naive ideas in science to reason scientifically. Naive ideas are indeed known to be more easily accessible and are reinforced in everyday situations. They plausibly rely on neural pathways with increased synaptic efficacy arising from repeated and persistent recruitment. Findings are also in close agreement with previous findings of stronger recruitment of IFG, MFG, and ACC for successfully overcoming naive ideas in science. Contrary to our hypothesis, the ACC didn’t show increased activity for incongruent compared to congruent statements in physics. In our study, the BOLD response in the ACC is modulated by the incongruency of statements in biology (Fig. 6a) which will be the topic of the next subsection.

Resisting naive ideas in physics also recruited more strongly the supplementary motor area that is usually associated with organizing and preparing voluntary movement, that is, the readiness for action. The left supplementary motor area would also play a more important role in controlling hand movements in right-handed individuals (in this study, our right-handed participants needed to press a button with the right hand). The anterior part of the supplementary motor area (the pre-SMA) is well known to be associated with inhibitory control, and is structurally connected to the IFG, a key region in inhibitory control. Moreover, increased demand on working memory and identification of meaning could have been more critical for reading incongruent statements, as evidenced by the higher activity found in the superior frontal gyrus and middle occipital gyrus. The first region is thought to particularly contribute to working memory. The second region is implicated in visual word form processing that includes the identification of shapes, letters, and words prior to, or in parallel to, identification of sound and/or meaning.

Congruent statements, for their part, showed increased recruitment of a focus in the right middle occipital gyrus. This region has been found to be involved in a diversity of networks, including spatial and semantic processing, but not in networks related to executive and inhibitory control. Therefore, our data provides evidence for a more automatic/perceptual processing of congruent statements by physicists, which is coherent with view of neural efficiency as a basis for optimal cognitive expertise with less and confined activations. Automatic processing of experts is associated with more selective brain areas that only manage the
One of the findings worth noting in the interaction analysis is that being confronted with naive ideas for which one possesses a basic versus an advanced level of expertise reveals rather separable activation patterns, but with notable overlapping activity in the IFG, pointing toward a central role for this brain area in processing interferences, including naive ideas in science, even for individuals having an advanced expertise. Indeed, the literature on IFG function specifically motivates its critical involvement in inhibitory control. Behavioral performance also supports the implication of inhibition as accuracy was significantly lower and response time slower for incongruent statements compared to congruent ones for the two levels of expertise. Yet, direct comparisons between biology and physics should be interpreted with caution as it could be allocated to other factors, including differences in the scientific content of the statements in the two areas. Furthermore, there are some inherent epistemological distinctions between physics and biology that could also cause the differences observed between biology and physics statements. Hence, it is unclear to what extent the brain activations comparing specific brain networks related to biology vs. physics are due to the level of expertise vs. the nature of the disciplines themselves and possibly other confounding factors including the respective curricula of the two disciplines. In addition, the time elapsed between physics and biology studies and the experiment differ greatly in our sample of physics experts, thus adding a confounding variable to the comparison of the two disciplines. Therefore, results regarding the expertise-dependent modulation of brain activity are not addressed directly in this study but are made available in Supplementary Material (see Supplementary Discussion—Main effect of expertise). Future study should address these limitations to better understand the inherent differences in brain-based mechanisms between advanced vs. basic expertise.

Although resisting to naive ideas in biology and physics reveal overlapping brain activations associated with inhibitory control, there is one significant difference. As evidence by the interaction effect between expertise and congruence, the main difference between physicists confronting naive ideas in physics and biology lies in the activity of the ACC. The direction of the interaction effect is driven by the contrast “incongruent > congruent statements” showing a higher BOLD response during the assessment of biology statements. As previously mentioned, the ACC is well known for its role in error detection and conflict monitoring82. According to this view, it appears plausible that the correct assessment of incongruent statements in both biology and physics requires inhibition. However, the certainty of the responses for incongruent statements in biology is lower since physicists are not advanced experts in biology and therefore, they are likely to have automated the processing of naive ideas in biology more than in physics due to lower exposure to scientific ideas in biology. The uncertainty might cause a stronger activation in the AAC. This interpretation is compatible with the literature on decision-making under uncertainty showing that when we have doubts about our responses, the ACC is more activated51. The recruitment of the IFG without a significant contribution of the ACC has been observed in situations about free falling objects in which inhibitory control is required, but in which there is no doubt about the correctness of the responses84. In sum, the main difference between physicists resisting to naive ideas in physics and biology doesn’t appear to be the involvement of inhibition, but the certainty of the provided responses.

It should be noted that one of the main limitations of this study is that the results are drawn from a reverse inference, where patterns of brain activity are used to infer the engagement of mental processes, such as inhibitory control, working memory, etc86. Contrary to a forward inference where, based on a given psychological manipulation, one can infer correlated changes in brain activity, reverse inference can be more problematic because...
several mental processes share similar neural patterns\textsuperscript{97}. Thus, when demonstrating the engagement of a mental process from a pattern of brain activity like it is done in this study, one should remember that the interpretation is still a hypothesis that would need to pass a rather higher standard of proof to be likely considered a conclusive finding\textsuperscript{86}. Nonetheless, although we share the view that reckless use of reverse inference is highly problematic, we also argue that reverse inference can have a predictive power and its reliability is dependent notably on the design of the cognitive task used as demonstrated in the revised formulation of reverse inference\textsuperscript{89}. Conditioning by task as we do here increases the predictive power of the presence of a specific cognitive process. For instance, in the case of this study, the experimental context didn’t focus on all activations associated with processing naive ideas in science, but rather activations associated with processing incongruent ideas in science more than congruent ideas in science. Nonetheless, we prudently recommended that these findings be treated with considerable caution.

To evaluate how persistent some naive ideas about natural phenomena are, we measured BOLD signals of 25 scientists with a Ph.D. in physics assessing the scientific value of incongruent and congruent statements, where naive ideas interfere with an appropriate scientific judgement or not, related to their domain of expertise (physics) and a domain, in which they have a more basic level of expertise (biology). In accordance to our hypothesis, the overall extent of activations for assessing incongruent statements was larger than for assessing congruent statements, especially in frontal areas, including IFG and MFG. Since these two brain regions are known to be involved in inhibitory control, and since the activations are observed for incongruent but not for congruent statements, these results suggest that inhibitory control could play a role when scientists with a Ph.D. in physics assess naive ideas in their field of expertise and in biology, where they have a more basic level of expertise.

Our findings might seem surprising since expertise is usually associated with neural efficiency, meaning less and confined activations. Through practice, processing becomes automatic requiring less effort and fewer procedural steps\textsuperscript{90–92}. However, while expertise is generally reflected by smaller and more selective brain areas\textsuperscript{99}, it is likely that even advanced experts have difficulty preserving cognitive resources when being confronted with deeply rooted naive science ideas. Indeed, they are likely to require increased active control to block unwanted thoughts that stem from naive ideas. This finding is in strong agreement with previous evidence from behavioral studies on the interference of naive ideas in scientific reasoning\textsuperscript{3,24,28,93} and neuroscientific studies on scientific expertise\textsuperscript{34,36,46}. Taken together, these results suggest that some naive ideas are extremely persistent, and probably never disappear, even after an extensive training, such as a Ph.D. in physics. Indeed, while certain early acquired ideas or stories appear to be more ephemeral, such as when children learn to differentiate between ordinary and magical events (e.g., moving a marble with one’s mind)\textsuperscript{99}, many naive ideas are different from those generally accepted by the scientific community and have proven to persist despite formal scientific instruction. They may persist because they are based on deeply anchored intuitions or heuristics\textsuperscript{14,53,28} or because they are more reinforced in everyday life contexts compared to scientific conceptions\textsuperscript{4,20,21}.

A finer grain analysis of the differences between processing naive ideas in biology and physics by scientists with a Ph.D. reveals that, while both seem to increase the activity of IFG and MFG, biology incongruent statements were associated with a specific increased activity in the ACC. Since this region can be associated with error detection, conflict monitoring, and decision-making under uncertainty, this activation could be related to the fact that, although physicists could successfully inhibit naive ideas in biology, they were not so sure about their answers in biology compared to physics. Therefore, it could be argued that error detection and the ACC plays a more significant role in basic expertise, but that, the necessity for conflict monitoring eventually decreases since naive ideas probably don’t prevail as much\textsuperscript{28}.

Altogether, our data reveals that a widely distributed network of frontal brain regions associated with executive functions and inhibitory control mediate the performance of experts, when judging the scientific value of statements related to naive science, whereas matched statements that do not relate to naive science hinge on a more selected and focal posterior brain regions associated with automatic processing of information. These results evidence a perspective according to which naive ideas of science are unlikely to be replaced by scientific ones and that, in the long run, conceptual change as it was initially described (a replacement of naive ideas with scientific ones) might never truly be achieved. Conceptual change might instead yield multiple ideas of each given natural phenomena, including scientific and naive ideas, which then have to be coordinated to demonstrate appropriate conceptual understanding. Instead, results encourage us to reconsider scientific expertise, suggesting that experts’ outstanding performance and success may be less an attainment and more a dynamic vigilance, allowing active control of thoughts when the context requires for it. In sum, this study is a springboard that lead to envision a larger scale study of expertise and conceptual change in sciences in different scientific fields. Future studies should also track changes in behavioral and brain activity, as novice participants gradually acquire expertise and experience conceptual change over time.

**METHODS**

**Participants**

We scanned a total of 25 right-handed adults who complete a Ph.D. in physics, including 23 male and 2 female participants (age range 28–60 years, $\bar{x} = 45$ years). The sample comprised university professors ($n = 17$), postdoctoral researchers ($n = 3$), senior high school (year 12 and 13), teachers ($n = 5$), and a developer–researcher ($n = 1$). All participants gave written informed consent and were duly compensated for their participation. None of the participants reported any abnormal neurological history. All experimental procedures were approved by the Research Ethics Board of Quebec’s Neuroimaging Network (CMER RNo. 13-14-023) endorsed by the Ministry of Health and Social Services of Quebec (Canada). We would like to acknowledge that there is a need for more studies to incorporate sex as a variable in experimental designs\textsuperscript{95}. The incapacity to explore these differences due to small sample size represents a limitation of this study, but can be largely explained by contextual factors beyond our control. Women remain underrepresented in physics. Although we have seen many improvements in the past decades, the percentage of women faculty in physics is, unfortunately, still stagnant at 12%\textsuperscript{96}.

**Behavioral task**

Participants were presented with naive ideas in a scientific statements task (see Supplementary Material—Supplementary Methods). On each trial, a short-written sentence was displayed for a 10-s period maximum during which the participants had to indicate whether the statement was scientifically correct or incorrect by pressing a button (Fig. 1a). Instructions stressed both speed and accuracy. They were given orally by the experimenter and then shown visually on the computer screen before starting the task. The task includes 128 scientific statements: 64 statements address phenomena in physics and 64 statements address phenomena in biology. Statements in the two scientific fields are equivalent for readability (Flesch index\textsubscript{Physics} = 75.7; Flesch index\textsubscript{Biology} = 70.2) as indexes for both domains are interpreted as “fairly easy to read — score 70.0–80.0,” corresponding to an average grade seven student’s written assignment\textsuperscript{97}. The statements in both domains are organized in pairs of incongruent and congruent statements matched on scientific content (concept) and level of analysis (macroscopic or microscopic). Congruent and incongruent statements were also equivalent in terms of response
Neurological Institute). Head motion was corrected with SPM8 across and within sessions of every individual subject. The fMRI series were corrected for motion using the standard SPM “spm_realign” procedure and mean images were calculated. Images are realigned to the mean image. Normalization was performed using the standard SPM “spm_coreg” procedure that co-registers the subjects T1 to their EPI and allows for a maximally similar normalization to the MNI template. The “single generative model” segmentation approach was employed to determine normalization parameters and used to normalize spatially the realigned images to the MNI reference space. This model involves alternates among classification, correction, and registration steps. The normalized EPI images were smoothed with a Gaussian kernel of 8 mm FWHM.

A two-level analysis was then implemented. For each participant, fMRI images were high-pass filtered for a cutoff at 128 s to remove low-frequency drifts. Then, the statistical analysis was conducted using the general linear model. Model time courses for each experimental condition block were generated on the basis of the hemodynamic response function implemented in SPM8. The analysis for the entire group was performed by computing linear t-contrasts (experimental conditions vs. fixation period) for each subject individually, which were then entered into random effects (second-level) whole-brain analysis of variance (ANOVA) using full factorial design analysis in SPM8. Described as a within-subject ANOVA with two within-subject factors of two levels each: EXPERTISE (basic vs. advanced) × CONGRUENCY (congruent vs. incongruent)\(^{101}\). Full factorial design is SPM terminology and refers to an option in the interface to specify the design matrix (and non-sphericity assumptions) of a GLM. The full factorial design analysis was used to model the main effect of CONGRUENCY and the interaction between EXPERTISE × CONGRUENCY to highlight differences in activation patterns between within-subject factors\(^{101}\). All brain activations resulting from the ANOVA are reported at the familywise error (FWE)-corrected threshold \(\text{P}_{\text{FWE, CORRECTED}} < 0.05\) across the whole brain, using a primary voxelwise threshold of \(\text{P}_{\text{UNCORRECTED}} < 0.005\) (in addition, a region of interest analysis can be found in Supplementary Material—Supplementary Discussion). Cluster-extent based thresholding can offer increased sensitivity to detect activations with large spatial extent to studies with moderate sample size\(^ {102}\). Despite some limitations, cluster-extent based thresholding has relatively high sensitivity\(^ {103,104}\) and takes into consideration the fact that voxel activations are not independent of the activations of neighboring voxels, especially when working with spatially smoothed data\(^ {105,106}\). Post hoc t-contrasts revealing the direction of the main effect and interaction (ANOVA) are reported using voxelwise threshold \(\text{P}_{\text{UNCORRECTED}} < 0.005\) to account for their lower statistical power compared to ANOVAs.

We used a primary voxelwise threshold of \(\text{P}_{\text{UNCORRECTED}} < 0.005\). Although Woo et al.\(^ {102}\) recommended, in general, using more stringent cluster-defining primary thresholds (\(\text{P}_{\text{UNCORRECTED}} < 0.001\) for a range of typical cases) to reduce the possibility of obtaining false positive clusters and to improve the degree of confidence in inferences about spatial specificity. Our choice is supported by the fact that Woo et al.’s\(^ {102}\) simulation was based on a sample of \(N = 33\), while in this study the sample is \(N = 25\), and that our hypothesis regarding the increased activity in IFG, MFG, and ACC areas does not require high spatial specificity like it is the case when studying smaller brain anatomical structures. However, although it appears reasonable to use a more liberal primary voxelwise threshold for this study, findings should be interpreted with some limitations in mind. Indeed, a more liberal cluster-defining primary threshold is associated with larger clusters spanning several anatomical structures\(^ {102}\). Therefore, one can only suppose that the activation is located within a significant cluster, but one cannot be confident about the statistical significance of specific locations within the cluster\(^ {102}\). In sum, one can’t reliably infer which brain regions show true effects within the significant cluster.

**Reporting summary**

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

**DATA AVAILABILITY**

The data that support the findings of this study are available on request from the corresponding authors (S.M. and G.A.D.). The data are not publicly available due the current legal provisions of Quebec (Canada) and in particular the Act respecting the protection of personal information in the private sector (L.R.C. (1985), ch. P-21, http://www.legisquebec.gouv.qc.ca/en/showdoc/cs/P-39.1).
CODE AVAILABILITY
The MATLAB script used for fMRI data preprocessing and statistical analysis is available from the corresponding author, upon reasonable request for purposes of reproducing or extending the analysis.

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AUTHOR CONTRIBUTIONS
Conceptualization, S.M., R.P., P.P., M.L. and G.A.D.; data curation, S.M. and G.A.D.; formal analysis, G.A.D. and S.M.; funding acquisition, S.M.; investigation, G.A.D. and L-M.B.F.; methodology, S.M., G.A.D., M.R., P.P. and M.L.; project administration, S.M., G.A.D. and L-M.B.F.; resources, S.M.; software, S.M.; supervision, S.M., G.A.D. and L-M.B.F.; validation, S.M. and G.A.D.; visualization, G.A.D. and S.M.; writing—original draft, G.A.D. and S.M.; writing—review and editing, G.A.D., S.M., M.R., P.P., M.L. and L-M.B.F. (based on CRediT: Contributor Roles Taxonomy, https://casrai.org/credit/).
COMPETING INTERESTS
The authors declare no competing interests.

ADDITIONAL INFORMATION
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