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Unveiling the neural mechanisms of supernatural fiction comprehension using fNIRS

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This study used fNIRS (functional near-infrared spectroscopy) to investigate the neural mechanisms underlying the processing of supernatural fiction, featuring either fictional or realistic characters, compared to real-world stories. Participants' brain activations were recorded while they read supernatural/realistic scenarios. Results showed that reading supernatural scenarios activated sensorimotor and the related frontal regions, compared to reading realistic scenarios. Furthermore, reading supernatural texts with unexpected realistic characters resulted in additional brain activity in the left IFG, compared to reading supernatural texts with expected fictional characters. Mediation analyses indicated that the activation of the left sensorimotor cortex during the reading of supernatural scenarios is mediated by readers' social cognition. Moreover, there was increased functional connectivity among different brain regions within the simulation network, and between the simulation network and the social cognition network, during the understanding of supernatural narratives. These findings suggest that simulation is crucial for readers to comprehend and interpret supernatural stories.

Literature is a powerful medium for expressing social and cultural nuances through language, and one of its key characteristics is its fictitious nature. Unlike factual accounts, fictional works transport readers to imaginary realms and allow them to immerse themselves in the lives of made-up characters. However, the extent to which readers are familiar with the story can impact their ability to connect with the characters and enter the fictional world. While previous research has examined the neural mechanisms involved in processing fictional and factual stories, it remains unclear how readers' knowledge of the fictional story and the characteristics of the characters influence their understanding of the narrative texts.

The main objective of this study is to investigate how the identification of fictional characters (such as those with expected fictional names like *Harry Potter* versus unexpected ordinary names like *John Smith*), affects narrative reading. Additionally, we aim to explore how individual differences in familiarity with the novel influence this process. By examining the neurocognitive processes associated with reading fictional narratives featuring real-world characters compared to fictional ones, we hope to gain insight into the complex workings of human cognition and its interaction with fictional narratives.

Research has explored the neural mechanisms involved in processing fictional versus factual stories, revealing distinct mechanisms underlying the comprehension of fictional and factual information^{1,2}. There are two

possible explanations for the observed neural differences when understanding a fictional story compared to a real-world story.

According to the simulation account^{3–5}, individuals rely on simulation to comprehend actions or events that cannot occur in reality. This theory suggests that people utilize different forms of simulation, such as perceptual, motor, and mentalizing simulation, to interpret the world around them⁶. Previous studies indicate that readers use their sensorimotor system to generate perceptual and motor simulations while processing descriptions of shape, orientation in texts^{7,8}, or actions^{9–11}. It is also suggested that readers use a similar brain system to mentally simulate abstract and complex events, such as the emotions and mental states of story characters, while engaging with novels^{3,5,12}. The simulation theory posits that individuals engage their sensorimotor system and associated brain networks (e.g., IFG) to mentally simulate events that they cannot physically enact¹³. Readers are required to mentally simulate the actions of fictional characters, particularly their supernatural actions, which is not always necessary with real-world actions. Research has demonstrated that the imagined actions and characters from fiction activate premotor/motor areas of the brain, similar to those engaged during the actual execution of comparable actions and perceptions^{14–16}. However, it remains unclear how readers adapt their perceptual and motor simulation strategies when encountering fictional worlds filled with supernatural characters and actions.

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On the other hand, an alternative explanation suggests that the observed differences in neural activity are not solely due to the simulation process itself, but rather to the difficulty associated with understanding fictional texts that challenge individuals' pre-existing knowledge, thus requiring heightened cognitive demands^{1,2,17,18}. For example, Filik and Leuthold found that if the information about the actions of a character contradicted the character's personality or beliefs (e.g., *Shaggy*, rather than *Scooby*, was depicted as the character in *the Scooby Doo* story who lifted a truck)¹⁹, it elicited increased N400 responses. Hsu and colleagues discovered that processing fictional characters and plots placed a greater burden on memory because they cannot be directly retrieved from episodic memory². More importantly, the deviation from real-world knowledge in a fictional narrative necessitates the involvement of additional brain regions responsible for attention and cognitive control (fronto-parietal control network), such as the lateral FPC/DLPFC¹ and inferior parietal lobule (IPL)². Therefore, further evidence is required to distinguish between these two explanations. Unlike previous investigations^{1,5,12}, the fictional materials utilized in our study exhibit supernatural behaviors that are completely implausible in the real world. This clear distinction between the fictional and real-world scenarios can lead to more definitive evidence in support of these arguments.

The reading experience of readers can significantly influence the process of reading fiction. It has been proposed that reading fiction serves as a form of social skills training²⁰. There are two main types of reading experiences to consider: general reading experience and the specific experience related to a particular novel or its characters. General reading experience reflects an individual's overall exposure to various reading materials and is often assessed by questionnaires such as the *Author Recognition Test* (ART)²¹. On the other hand, the experience with a specific novel or its characters focuses on the reader's deep engagement with that particular piece of fiction.

Research shows a strong connection between reading experience and social cognition. Various studies have shown that reading fiction can lead to significant improvements in social cognitive abilities such as Theory of Mind, empathy, and perspective taking^{22,23}, though some studies have failed to find significant effects^{24,25}. Recent meta-analyses further support this association, indicating that frequent reading of fiction is linked to higher levels of empathy and Theory of Mind skills^{26,27}. Hartung and Willems discovered a positive correlation between reading fiction and the connectivity of brain regions involved in understanding others' intentions, beliefs, and emotions²⁸. Their findings suggest that individuals who read fiction more regularly have enhanced connections between specific brain areas linked to social cognition and language processing, such as the bilateral IFG, the right MFG (middle frontal gyrus), the posterior part of the right supramarginal gyrus (SMG), and the anterior section of the medial prefrontal cortex (mPFC).

Interestingly, the positive impact of reading experience on social cognition seems to be influenced by readers' active engagement with the story. Bal and Veltkamp found that the beneficial effects of reading novels on social cognition were only noticeable when readers were fully immersed in the narrative²⁹. In one fMRI study, Broom and colleagues examined whether identification with fictional characters leads to increased neural overlap between the self and fictional characters³⁰. Participants who reported a stronger identification (more familiar) with fictional characters exhibited more overlap in neural activity between themselves and these characters.

In summary, previous studies have largely focused on how reading fiction (compared to non-fiction) influences social cognition, often through correlational approaches. However, it is also possible that there is a reverse causal relationship, where an individual's social cognition actively influences their choice of reading material, possibly drawing socially adept individuals more towards fiction due to its social contexts. Therefore, it remains unclear how individual differences in social cognition impact novel reading, particularly in genres like supernatural fiction.

The present study aims to illuminate the neural underpinnings of comprehending fictional narratives, particularly focusing on the interplay between readers' reading experience and supernatural understanding. To

achieve this, we will explore how readers' knowledge of fictional characters influences their comprehension of supernatural literature. We will compare the responses of two groups of readers, one familiar with the HP story (the high-familiarity group) and one unfamiliar (the low-familiarity group), as they read both supernatural and realistic scenarios within the HP literary universe. Participants will be asked to read two different types of fictional scenarios. The first type will include supernatural elements directly from the HP series. The second type will also contain supernatural elements, but the original characters (e.g., *Harry Potter*) will be replaced with realistic names like *John Smith*, while keeping the supernatural scenarios unchanged. A pivotal aspect of our research involves the introduction of the "supernatural scenarios with realistic characters". This unique condition, where familiar supernatural landscapes accommodate characters with ordinary, realistic names like *John Smith* serves as a controlled probe into the cognitive effects of character-world incongruity. Both types of supernatural scenarios will then be contrasted with realistic scenarios where no supernatural powers are present (control condition). By comparing reader responses to expected, fantastical personas with those of unexpectedly realistic characters embedded in supernatural storylines, we aim to uncover not only the neural basis underlying the reading of supernatural fiction versus realistic fiction, but also how the inconsistency between characters and the fictional world impacts the comprehension of supernatural literature.

Compared to previous studies on fictional reading, our study offers several advancements. Firstly, previous research has revealed the neural differences between the processing of fictional and factual texts, but it has not explored how the characteristics of the characters in fictional scenarios influence novel reading. Moreover, existing neuroimaging studies did not explore how fictional reading is influenced by the reader's familiarity with the specific fictional story. Thirdly, existing studies on the neural basis of processing supernatural narratives mainly employed between-item designs. Although researchers have managed to control for potential confounding factors at the lexical (e.g., word frequency) and sentence levels (e.g., sentence structures, sentence complexity²), it has been challenging to match these texts at higher levels, such as narrative complexity and transportation, since there are numerous factors within the text itself that may influence readers' actual responses when processing such texts. In contrast, our study employs a within-item design by extracting all materials from the HP Collection and ensuring that narrative texts in each of the three conditions are based on the same scenario, with the only difference being the names of fictional characters or the specific actions they perform.

Based on previous relevant studies^{3,13,31}, we hypothesize that if the difference in reading fictional novels (compared to factual narratives) arises from the process of simulation, we expect to observe an increase in brain activity in core areas responsible for simulation operations, such as the sensorimotor cortex (e.g., preCG: precentral gyrus; poCG: postcentral gyrus) and its adjacent parts (e.g., IFG)^{32–34}. This effect should be particularly pronounced in supernatural scenarios—both those featuring fictional characters (SF) and those featuring realistic characters (SR)—compared to realistic scenarios with realistic characters (RR). Additionally, we expect heightened functional connectivity within the simulation network and between this network and other systems involved in discourse comprehension, such as the theory of mind (ToM) network, as readers mentally simulate the behaviors described in supernatural stories (SF and SR) more than in realistic ones (RR). Notably, we also predict that the brain regions supporting simulation will be more strongly engaged in SR than in SF. This is likely because supernatural behaviors performed by a realistic character are unpredictable, making the simulation process more challenging to initiate.

Alternatively, if the difficulty in processing supernatural narratives arises from the need to integrate inconsistencies into existing world knowledge or exert greater cognitive control over these inconsistencies, we expect stronger activation in brain regions responsible for cognitive control and integrative processing, as well as increased connectivity between these regions, in SF and SR compared to RR. These regions may include the lateral frontopolar cortex (FPC) and dorsolateral prefrontal cortex (DLPFC)¹, as

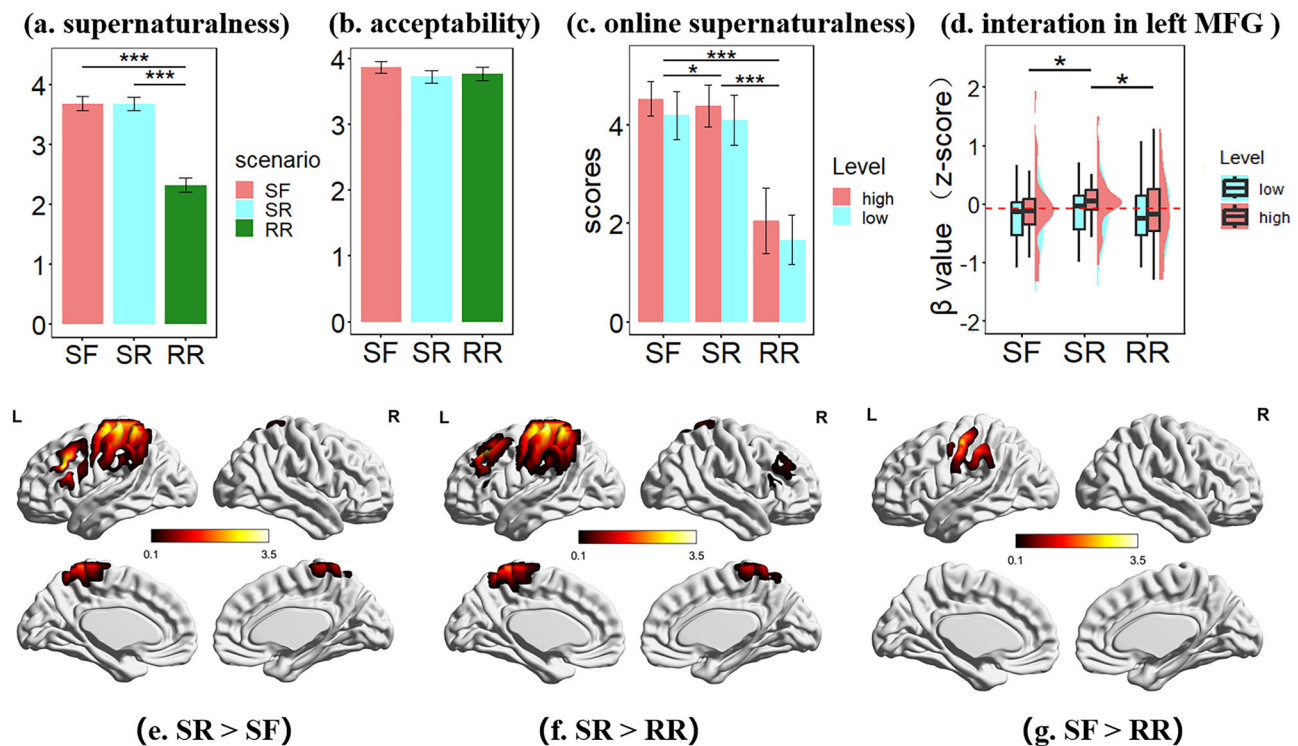


Fig. 1 | Results of behavioral ratings and brain activation. **a** Results of the supernaturalness rating test and **(b)** the acceptability test for each of the three experimental conditions (SF: supernatural scenarios with fictional characters, SR: supernatural scenarios with realistic characters, and RR: realistic scenarios with realistic characters). **c** Online supernaturalness judgment scores for readers with low

and high familiarity with HP. **d** HbO activity recorded during the reading of each of the three experimental scenarios in the left MFG region at CH1 for readers with low and high familiarity with HP. **e–g** Brain regions activated when comparing each pair of experimental conditions (e: SR vs. SF; f: SR vs. RR; g: SF vs. RR).

well as the inferior parietal lobule (IPL)². However, under this hypothesis, we do not expect heightened activity in the simulation network or increased functional connectivity within it. Importantly, this cognitive processing effect should occur regardless of readers' familiarity with the Harry Potter series, as supernatural scenarios inherently contradict common knowledge.

Considering individual differences in fiction reading, we propose that brain activity patterns during fiction reading will be influenced by readers' familiarity with the narrative. Individuals with greater familiarity are more likely to become immersed in the fictional world^{29,30}. Specifically, those with a deeper understanding of the Harry Potter series are expected to engage in more extensive simulation of character actions compared to those with limited knowledge. As a result, readers should exhibit greater reliance on the simulation network in SF and SR relative to RR, along with stronger functional connectivity within the simulation network in the high-familiarity group compared to the low-familiarity group. Finally, given the well-established role of fiction reading in enhancing social cognition^{23,26,27}, and the demonstrated close relationship between imagination and simulation^{35–37}, we hypothesize that social cognition (e.g., imagination, social skills, and communication) plays a crucial role in supernatural story processing. It may also mediate the relationship between supernatural reading and brain activation.

Results

Behavioral Results

Similar to the norming test, we employed linear mixed-effects models (LMMs) using the lmerTest package in R (version 4.2.1, 2022) to analyze differences in online supernaturalness ratings across different scenarios and familiarity levels. The analysis revealed a significant main effect of Familiarity ($\chi^2 = 12.118$, $df = 1$, $p < 0.001$; see Fig. 1c). Post-hoc comparisons using the emmeans package with FDR correction showed that participants with high familiarity consistently rated all types of scenarios significantly higher than those with low familiarity ($\beta = 0.342$, $t(59) = 3.493$, $p_{FDR} < 0.001$). In

addition, Scenario Type also showed a significant main effect ($\chi^2 = 166.93$, $df = 2$, $p < 0.001$). Follow-up analyses revealed that participants rated SF significantly higher than RR ($\beta = 2.508$, $t(60) = 28.383$, $p_{FDR} < 0.001$) and SR ($\beta = 0.131$, $t(60) = 2.811$, $p_{FDR} = 0.027$). Moreover, SR was rated significantly higher than RR ($\beta = 2.407$, $t(60) = 28.319$, $p_{FDR} < 0.001$).

Brain activation

The group level activation showed a significant main effect of Scenario Type (see Supplementary Table 2). As depicted in Fig. 1e–g (also refer to Table 1), further analysis showed that participants exhibited significantly higher activation in the left preCG (CH2), poCG(CH3) and IFG (CH13) when reading SR compared to SF. Additionally, participants displayed significantly higher activation in the left preCG (CH2), poCG(CH3), MFG (CH8) when reading SR compared to RR. Moreover, there were marginally significant stronger activations in the left poCG (CH10) when reading SF compared to RR.

Importantly, there was a significant interaction between Scenario Type and HP familiarity at the left MFG [CH1: $\chi^2 = 15.2$, $df = 2$, $p_{raw} < 0.001$, $p_{FDR} < 0.001$]. As shown in Fig. 1d, subsequent emmeans analysis revealed that the high-familiarity group showed significantly higher activation during the reading of SR compared to RR [$t(118) = 3.99$, $\beta = 0.884$, $p_{FDR} < 0.001$] and higher activation during the reading of SR compared to SF [$t(118) = 3.85$, $\beta = 0.852$, $p_{FDR} < 0.001$]. In contrast, the low-familiarity group did not exhibit significant activation differences in any comparisons.

The correlation analyses revealed a significant positive correlation between the supernaturalness ratings and the activation difference of SR and SF in the Left poCG (CH3) ($r = 0.058$, $t(2560) = 2.93$, $p_{raw} = 0.003$, $p_{FDR} = 0.028$; See Fig. 2a).

Mediation analysis

In order to further investigate the potential role of individual differences in social cognition, measured by AQ (S-C-I), on the relationship between

Table 1 | Brain activations resulting from different contrasts were examined, and both uncorrected (raw) p -values and false discovery rate (FDR) corrected p -values were reported

Scenario type	Channel	Region (AAL)	β (absolute value)	t (absolute value)	P_{raw}	P_{FDR}
SR > SF	CH2	preCG.L	0.71	3.39	<0.001	0.010
	CH3	poCG.L	0.89	3.73	<0.001	0.006
	CH13	IFGoperc.L	0.68	3.51	<0.001	0.009
SR > RR	CH2	preCG.L	0.70	3.32	0.001	0.017
	CH3	poCG.L	0.94	3.96	<0.001	0.003
	CH8	MFG.L	0.51	3.13	0.002	0.024
SF > RR	CH10	poCG.L	0.67	3.27	0.001	0.061

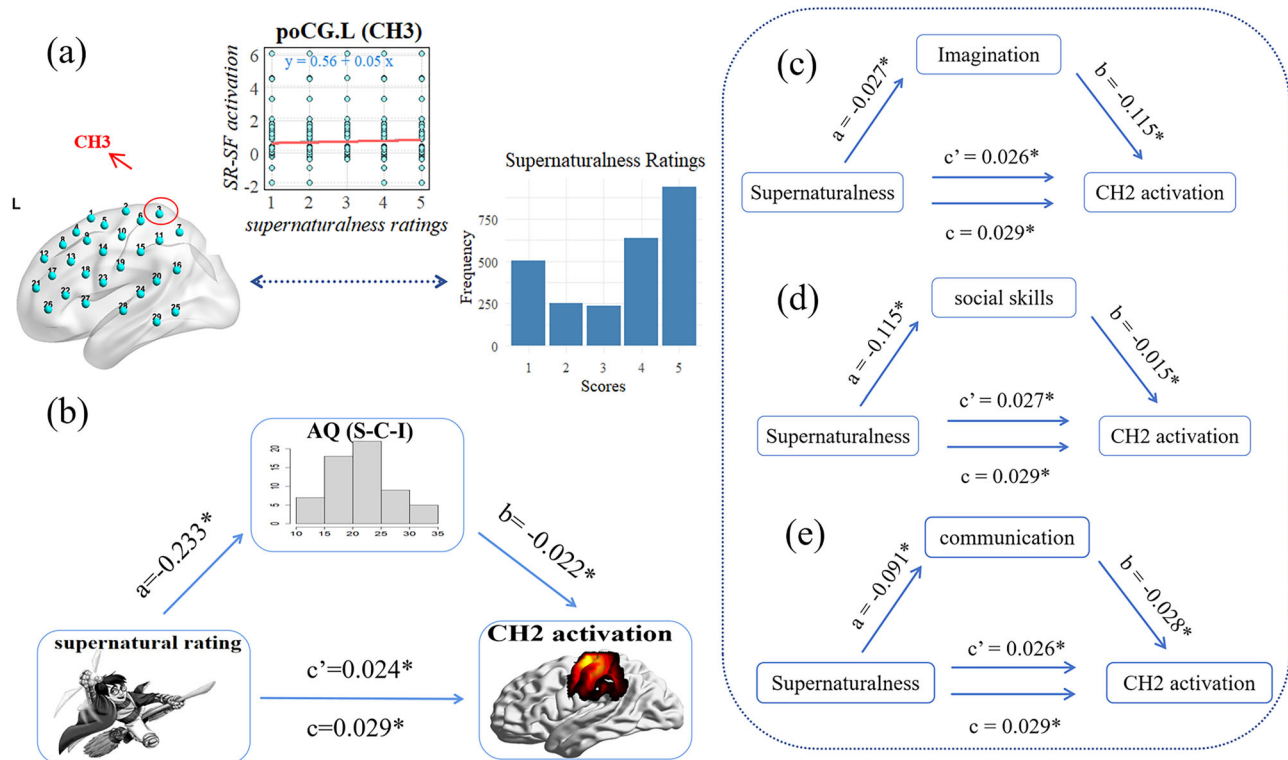


Fig. 2 | Results of correlation analysis and mediation analysis. **a** Significant positive correlation between supernaturalness ratings and the activation difference between SR and SF in the left PoCG (CH3). **b** AQ (the average of the three AQ subscales directly related to social cognition: social skills, communication, and imagination) partially mediates the relationship between participants' supernaturalness ratings and brain activation in the Precentral Gyrus (preCG) at channel CH2. **c–e** Imagination, social skills, and communication (the three AQ subscales) partially mediate the relationship between participants' supernaturalness ratings and brain activation in the preCG at

channel CH2. Path a represents the relationship between supernatural rating and the mediator (AQ or subscales of AQ). Path b represents the relationship between the mediator (AQ or subscales of AQ) and the brain activation, without considering supernatural rating. Path c represents the total effect of supernaturalness ratings on brain activation, without considering the mediator. Path c' represents the direct effect of supernaturalness ratings on brain activation after introducing the mediator. Asterisks (*) indicate significant paths, and the value preceding the asterisk denotes the effect size corresponding to each path.

supernatural rating and brain activation in interesting regions, a series of regression analyses were conducted on the trial-level data. As shown in Fig. 2b, the results from the left preCG (CH2) indicated that for the supernatural scenarios with fictional characters (SF), the ratings of supernaturalness were significantly associated with brain activation (path c : $\beta = 0.029$, $t(2560) = 3.92$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$), as well as with S-C-I scores (path a : $\beta = -0.233$, $t(2560) = -7.13$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$). Additionally, a significant association was also found between S-C-I scores and brain activation in the preCG (path b : $\beta = -0.022$, $t(2559) = -8.42$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$). Importantly, when controlling for AQ, there was also a significant correlation between supernatural ratings and brain activation (path c' : $\beta = 0.024$, $t(2559) = 3.24$, $p_{FDR} = 0.037$, $p_{raw} = 0.001$), suggesting that AQ partially mediates the relationship between supernatural reading and brain activation in the left sensorimotor cortex.

Interestingly, as shown in Fig. 2c–e, when the AQ subscales were used in the mediation analysis instead of the overall S-C-I score, the same pattern of results was observed for *imagination*, *social skills*, and *communication*.

Imagination

The on-line ratings of supernaturalness were significantly associated with brain activation (path c : $\beta = 0.03$, $t(2560) = 3.92$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$), as well as with imagination scores (one of subscales of AQ) (path a : $\beta = -0.03$, $t(2560) = -2.60$, $p_{FDR} = 0.009$, $p_{raw} = 0.009$). Additionally, a significant association was also found between imagination scores and brain activation in the preCG (CH2; path b : $\beta = -0.12$, $t(2559) = -14.21$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$). Importantly, when controlling for imagination, there was also a significant correlation between supernatural ratings and brain activation (path c' : $\beta = 0.03$, $t(2559) = 3.55$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$).

Social skills

The ratings of supernaturalness were significantly associated with brain activation (path c: $\beta = 0.03$, $t(2560) = 3.92$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$), as well as with social skills scores (path a: $\beta = -0.12$, $t(2560) = -6.10$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$). Additionally, a significant association was also found between social skills scores and brain activation in the preCG (CH2; path b: $\beta = -0.02$, $t(2559) = -3.33$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$). When controlling for social skills, there was also a significant correlation between supernatural ratings and brain activation (path c': $\beta = 0.03$, $t(2559) = 3.68$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$).

Communication

The ratings of supernaturalness were significantly associated with brain activation (path c: $\beta = 0.03$, $t(2560) = 3.92$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$), as well as with communication scores (path a: $\beta = -0.09$, $t(2560) = -6.49$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$). Additionally, a significant association was also found between communication scores and brain activation in the preCG (CH2; path b: $\beta = -0.03$, $t(2559) = -4.74$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$). When controlling for communication, there was also a significant correlation between supernatural ratings and brain activation (path c': $\beta = 0.03$, $t(2559) = 3.56$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$).

Functional connectivity analysis

The analysis of functional connectivity, using the Phase Locking Value (PLV), revealed strong connectivity between the left poCG (CH10) and the left IFG (CH22) when comparing SR to SF ($t(60) = 19.766$, $sd = 0.171$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$). Moreover, significant connectivities were observed between the left poCG (CH10) and the left IFG (CH22) ($t(60) = 14.718$, $sd = 0.173$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$), as well as between the right angular gyrus/AG (CH32) and the right IFG (CH41) when comparing SR to RR ($t(60) = 14.925$, $sd = 0.139$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$), as shown in Fig. 3a. Further analyses were conducted on participants with different HP levels. Among the high-familiarity group, participants exhibited significantly higher PLV in connections between the left MFG (CH21) and the right poCG (CH31) ($t(30) = 12.504$, $sd = 0.191$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$), as well as between the left preCG (CH5) and the right AG (CH32) ($t(30) = 12.516$, $sd = 0.204$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$) when comparing SR to SF. Moreover, significant connectivities were observed between the left IPL (CH7) and the right SPG (CH36) ($t(30) = 12.752$, $sd = 0.205$, $p_{FDR} < 0.001$, $p_{raw} < 0.001$) when comparing SR to RR (see Fig. 3b). However, no significant differences were found in the low-familiarity group.

Discussion

The present study aimed to investigate the neural mechanisms underlying the processing of supernatural events, as well as how these mechanisms are influenced by readers' familiarity with the novel. The study yielded the following main findings. Firstly, our findings reveal significant activation in the sensorimotor cortex, particularly in the left precentral gyrus (preCG) and postcentral gyrus (poCG). The group level analysis revealed that reading supernatural scenarios elicited greater activation in the left poCG, compared to reading real-world narrative scenarios. Similarly, reading supernatural texts containing unexpected realistic characters resulted in stronger activations in the left preCG, poCG and IFG compared to reading supernatural texts featuring expected fictional characters. We also found that readers familiar with HP stories demonstrated the same pattern as the group level analysis, while no notable difference in brain activity was observed between these conditions among individuals who were unfamiliar with the HP stories (see Supplementary Table 3). Thirdly, mediation analysis revealed that S-C-I scores partially mediate the relationship between supernatural rating and brain activity in the left preCG. Lastly, group-level functional connectivity analysis showed increased connectivity between the left poCG and left IFG when comparing a supernatural scenario with realistic characters (SR) to a supernatural scenario with fictional characters (SF) or to a realistic scenario with realistic characters (RR). Notably, high-familiarity readers exhibited increased functional connectivity between the

left preCG and the right AG, as well as between left MFG and the right poCG when comparing a supernatural scenario with realistic characters with a supernatural scenario with fictional characters. Additionally, they exhibited increased functional connectivity between the left IPL and the right SPG in the comparison of supernatural scenarios featuring realistic characters to realistic scenarios featuring realistic characters (i.e., realistic scenarios).

Previous literature has argued that people understand fiction by using simulation to engage them into the story. However, other researchers propose that the disparity between reading fictional and realistic stories is primarily attributed to cognitive complexity. In this study we found that reading supernatural stories activates various regions in the left hemisphere of the brain. Among these regions, the left pre/poCG plays a crucial role. This is likely because supernatural novels, such as *Harry Potter*, involve numerous magical actions and movements (e.g., *Harry passing through a wall, riding a broom*). Consequently, readers rely more heavily on their sensorimotor system to mentally simulate these actions compared to other reported novels (e.g., *The Little Prince*⁴). This is further supported by the increased connectivity between the left poCG and the left IFG when comparing supernatural scenarios to realistic ones. Moreover, participants' social cognition abilities such as imagination and social skills mediates the relationship between understanding supernatural narratives and brain activity in the left preCG. An alternative explanation is that these increased activations and strengthened connectivity may stem from the processing of conflicting information relative to prior knowledge. Previous studies have demonstrated that inconsistencies with existing world knowledge activate the left inferior prefrontal cortex¹⁷. While we cannot entirely rule out this possibility, we consider it less likely. If these neural modulations were driven by world-knowledge inconsistency, we would expect a similar pattern of activation regardless of the reader's familiarity with *Harry Potter* stories. However, our results showed that increased brain activations in premotor cortex (see Supplementary Table 3) and the strengthened functional connectivity between key brain regions occurred only in highly familiar readers when comparing SR to RR and SR to SF conditions, but not in low-familiarity readers. This selective effect strengthens our interpretation that the observed brain activity reflects simulation rather than mere semantic conflict.

These results provide direct evidence for the simulation account^{3–5}, which proposes that reading fictional novels involves the activation of the motor cortex and the projected regions to mentally simulate the actions described in the fictional story. Previous studies have demonstrated that the motor cortex (including pre/poCG) is typically associated with observing others performing actions⁵, but it is also consistently activated when watching films or reading fictional narratives^{3,4,15}. This aligns with the predictive model of the sensorimotor system, which suggests that the sensorimotor system can be generalized from actions to events and people default to using their sensorimotor system in a simulation mode for predicting events that will occur within a few seconds, particularly events that they cannot reproduce or imitate (such as supernatural events¹³).

Overall, these findings contribute to our understanding of the role of the sensorimotor cortex in action and event prediction and support the idea that understanding fictional stories occurs through the mechanism of simulation.

An unforeseen occurrence involving realistic characters in a supernatural context presents a contradiction to our current knowledge and particularly to those well acquainted with the fictional narrative. Our investigation revealed that when engaging with supernatural texts featuring unexpected realistic characters, such as the replacement of *Harry Potter* with an ordinary character like *Zhong Xing*, there was a heightened activation observed in the left pre/poCG and IFG, in contrast to reading texts involving anticipated fictional characters.

According to the simulation account^{3,13}, individuals are able to mentally simulate events that they are unable to physically reproduce. Readers should possess the ability to naturally simulate supernatural actions performed by fictional characters. However, it may prove more challenging for them to simulate a supernatural action when it is performed by a realistic character rather than a supernatural one. This is because a realistic character

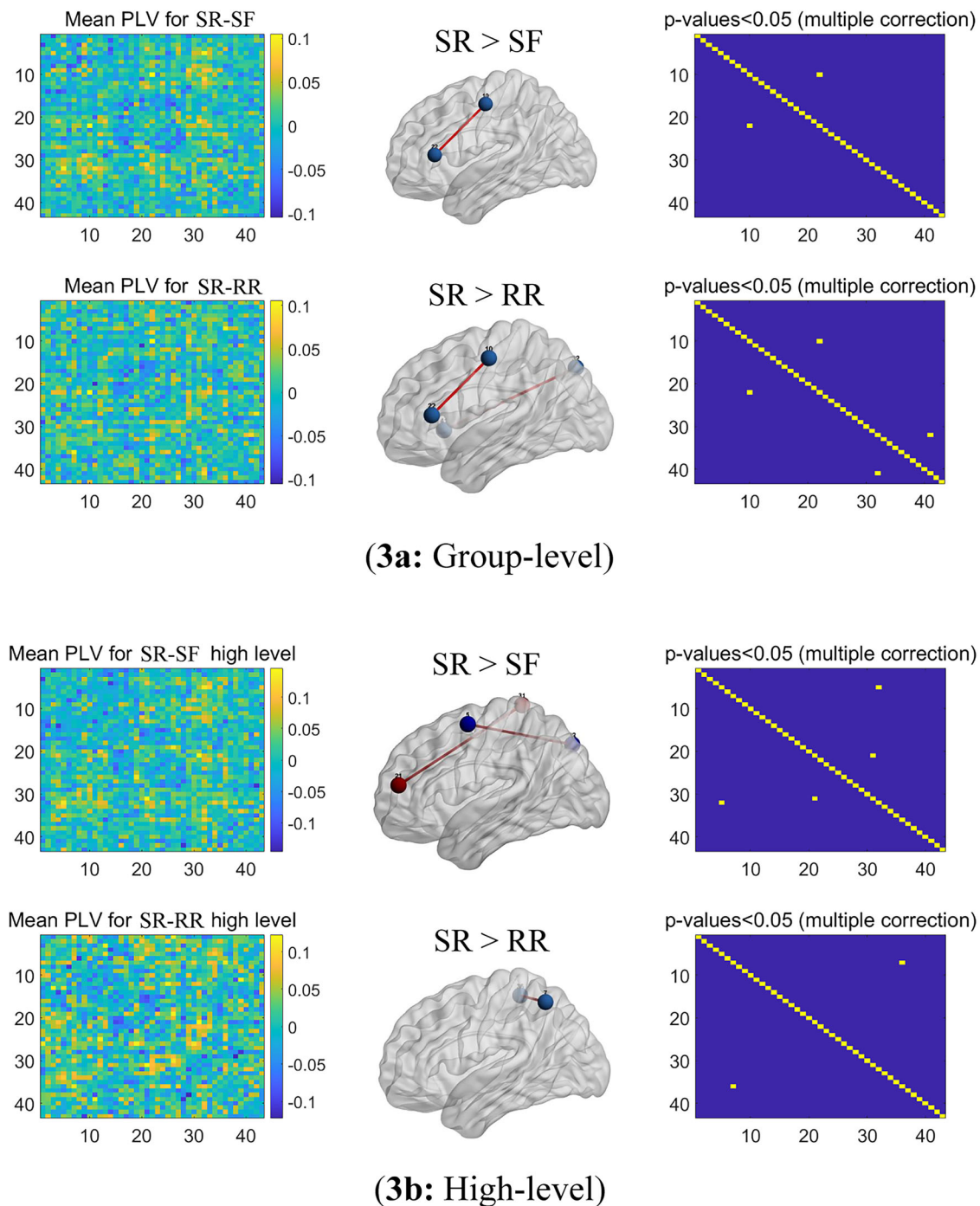


Fig. 3 | Results of functional connectivity. **a** In the group-level analysis, there was increased connectivity between the left poCG and left IFG when comparing SR to SF or SR to RR. There was increased connectivity between the right AG and the right IFG when comparing SR to RR. **b** In the high-familiarity group analysis, there was

increased connectivity between the left preCG and the right AG, as well as between the left MFG and the right poCG when comparing SR with SF. Furthermore, there was increased connectivity between the left IPL and the right SPG when comparing SR to RR.

performing a supernatural action not only goes against the rules of the real world but also contradicts the rules of the fictional world. This inconsistency may require additional effort for the simulation network to function. An increase in activation in the sensorimotor cortex and stronger functional connectivity between the sensorimotor cortex and other prefrontal and parietal regions have been implicated.

These findings suggest that the presence of unexpected elements in a supernatural narrative can pose challenges for the functioning of the simulation system. Additionally, it also suggests that readers who possess a greater familiarity with the HP story are more inclined to actively engage

with the storyline and mentally simulate the supernatural phenomena. This provides further support for simulation theory as an explanation of how readers process supernatural fiction.

Understanding fictional stories requires not only comprehending the meaning of words, phrases, and sentences but also the ability to infer the behaviors, feelings, and mental states of fictional characters, as well as predict upcoming characters and plot developments^{31,38}. Variations in a reader's social cognition can influence the process of reading novels^{4,31,39}. In this study, we explored how individual differences in social cognition affect novel reading and simulation.

Our mediation analysis supported the role of social cognition in reading fiction, showing that activation of the left premotor cortex (e.g., preCG) during supernatural scenarios was mediated by social cognitive abilities, including social skills, imagination, and communication, as measured by the AQ test (S-C-I scores). Further analysis revealed that each of these subscales partially mediated the relationship between supernatural reading and brain activation in the preCG. The AQ test is widely used to assess the presence of *Autism Spectrum Traits* in adults³⁴. Previous fMRI studies have shown that individuals with *Autism Spectrum Disorder* (ASD), who exhibit deficits in these cognitive abilities, demonstrate a unique impairment in embodied simulation^{40,41}, highlighting a strong overlap between social cognition and simulation. Among the subscales, imagination plays a particularly crucial role in simulation. It enables individuals to generate, manipulate, and experience mental representations of events, actions, and scenarios that are not presently occurring^{35,36}. In the context of fiction reading, the vividness of supernatural actions heavily depends on readers' imaginative capacities. In this study, we found that imagination (along with other social cognitive abilities) significantly influenced supernatural reading and mediated the relationship between online supernatural reading and activation in the simulation network. This suggests that imagination, together with other social cognitive abilities, is key to simulating the mental states of others during supernatural reading.

Given the importance of the simulation system in understanding supernatural narratives, these findings suggest that individual differences in social cognition play a key role in modulating neural processes within the simulation network, facilitating the understanding of supernatural narratives. Previous research has established a strong link between simulation and fiction reading^{3,5,6,12}, and our study further highlights the mediating role of readers' social cognition in this relationship.

We made an intriguing discovery pertaining to the functional connection between the left poCG and IFG during the analysis of different narrative scenarios. Specifically, we found that the connection between the poCG and IFG plays a crucial role in comprehending supernatural events as well as understanding unexpected characters. This finding aligns with the predictive accounts of the sensorimotor system, which propose that the sensorimotor system not only facilitates the execution of actions, but also aids in the perception of events¹³. Individuals are able to effectively utilize their sensorimotor system and the projected areas to mentally simulate events that they are unable to physically replicate, including supernatural occurrences. Moreover, people can predict the actions of others by relying on their simulation system. The IFG, in particular, is integral to predicting goals and has connections with the motor cortex. The motor cortex is believed to be involved in predicting changes or movements, while the IFG is involved in predicting goals^{13,42}. Previous studies have showed that both the premotor/supplementary motor cortex and IFG play important role in simulation, especially in simulation of actions and perception^{32,34,36}. In line with this interpretation, the connection between the sensorimotor cortex and IFG is critical for predicting both actions and events. Lehne and colleagues found that reading a suspenseful literary text significantly increased the functional connectivity between the left IFG and left premotor cortex¹⁵, which was interpreted as reflecting the prediction of actions and events. In the present study, we also observed heightened connectivity between the sensorimotor area and the left IFG. The heightened connectivity between these areas when processing supernatural events, compared to realistic events, could be attributed to the simulation of actions that participants cannot physically reproduce (e.g., *Harry passing through a wall*).

The readers' familiarity with the HP story can influence brain connectivity. In high-familiarity readers, we observed heightened connectivity between the left preCG and right AG, as well as between the left MFG and right poCG, when supernatural behavior was performed by a realistic character as opposed to a fictional character. Additionally, increased connections were also found between the left IPL and right SPG when comparing unexpected supernatural scenarios with realistic control scenarios. These extensive connections suggest that high-familiarity readers, due to their enhanced familiarity with the story, are able to make strong predictions

about supernatural actions performed by expected fictional characters (e.g., *Harry Potter*). However, when faced with the introduction of a realistic character, their simulation process becomes more challenging. The involvement of additional brain networks between the two hemispheres may reflect the effort to reconcile the inconsistency between expected fictional characters and the characters who actually performed the action, and subsequently initiate the simulation process. In contrast, low-familiarity readers did not exhibit significant connectivity, further suggesting that the strengthened functional connections in high-familiarity readers cannot be attributed solely to cognitive difficulty or conflict. If cognitive conflict were the driving factor, similar patterns of connectivity would be expected for easily recognizable supernatural behaviors (e.g., *a person rushing through a wall*) in both groups. Instead, the results imply that high-familiarity readers can more readily initiate the simulation of supernatural behaviors. Their familiarity with the HP story may provide a cognitive advantage, as they have developed a well-established network of interconnected brain regions that facilitates efficient simulation. Nevertheless, the introduction of a realistic character appears to diminish this cognitive advantage, making it more difficult for the simulation system to function effectively.

Although the present study provides clear evidence for the important role of simulation in understanding supernatural stories and demonstrates that social cognition may mediate the association between fictional reading and simulation mechanisms, it is important to acknowledge several limitations. First, although the offline questionnaires, brain activations, mediation analysis, and functional connectivity results offer converging evidence for the simulation account of supernatural reading, we did not explicitly measure the extent to which participants mentally simulated the actions or behaviors of the story characters during fNIRS data collection. This limits our ability to directly investigate the relationship between brain activity and simulation behavior. Second, social cognition in this study was assessed using self-reported questionnaires. Future research should consider employing more objective methods to assess social cognition. Moreover, while this study primarily focused on the cognitive aspects of reading fiction, emotional responses to stories may also play a significant role in simulation processes. Future research could explore the interplay between emotional engagement with fiction and simulation mechanisms to provide a more comprehensive understanding of the effects of reading on cognitive processes. Additionally, exploring how individual differences in emotional responses to fiction influence mental simulation could offer valuable insights into the complex relationship between fiction reading and cognitive mechanisms.

In summary, this study presents compelling evidence that the simulation network, which includes the perception and motor cortex, along with other related frontal areas, is significantly involved in the processing of supernatural scenarios in comparison to realistic scenarios. The mediation analysis demonstrated that the activation of the left sensorimotor cortex during the reading of supernatural scenarios is influenced by readers' social cognition abilities. Additionally, the study identified increased functional connectivity among different brain regions within the simulation network, as well as between the simulation network and the social cognition network during the understanding of supernatural narratives, as opposed to realistic ones. These findings suggest that readers rely on simulation to comprehend and interpret supernatural storytelling.

Methods

Participants

A statistical power analysis was conducted before the experiment using the G*Power 3.1.9.7 statistical analysis program in order to estimate the sample size⁴³. With a Type I error rate of 0.05 ($\alpha = 0.05$) and a Type II error rate of 0.05 ($1 - \beta = 0.95$), the projected total sample size was determined to be 44 based on the expected effect size of 0.25 ($f = 0.25$) according to our experimental design (see below). Sixty-seven participants were recruited in this study. Data from six participants were excluded due to an accuracy rate below 70% on comprehension questions (fillers) during the formal experiment, resulting in a final sample of sixty-one participants. These

remaining participants were divided into two groups based on their HP familiarity scores from the pre-experiment norming test. The HP familiarity test consisted of four subsets: HP film (eight films in all, one point awarded for watching one of the eight films each time), HP fiction (seven books in all, one point awarded for reading one of the seven books each time), HP self-rating (ranging from 0 to 10 points), and HP trivia quiz (thirty multiple choice questions about the HP wizarding world, one point awarded for one correct answer). The high-familiarity group had thirty participants (eight males, *Mean age* = 23.53, *SD* = 1.72, range = 18–27) while the low-familiarity group had thirty-one participants (two males, *Mean age* = 23.64, *SD* = 1.43, range = 21–28). The high-familiarity group had a mean HP score of 49.07 (*SD* = 13.01, range = 29–90) while the low had a mean score of 1.00 (*SD* = 1.03, range = 0–4). All participants were native Chinese speakers, right-handed, with normal or corrected-to-normal vision, and had no history of brain injury or reading disorders. Participants gave informed consent before the experiment and they would be paid after finishing the experiment. This experiment was carried out in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Nanjing Normal University (IRB: 202007005).

Design and materials

The present study had a 3 × 2 mixed design, with *Scenario Type* (SF: supernatural scenarios with fictional characters, SR: supernatural scenarios with realistic characters, and RR: realistic scenarios with realistic characters) as a within-subject factor and *HP familiarity* (high vs. low) as a between-subject factor. Forty-two scenarios were selected from the Mandarin Chinese translations of seven HP novels. SF were the excerpts from the original HP novel, whereas SR involved modifying the character's name (for example, changing "Harry" to "Zhong Xing," a real name). RR differed from SF by not only changing the character's name but also altering the events to be realistic (replacing supernatural elements and events with normal ones; see examples below). Consequently, SF and SR were essentially identical, except for the character's name. SF and RR were identical, apart from the character's name and the supernatural action the character took. Similarly, SR and RR were also identical, except for the supernatural action performed. Each scenario consisted of two parts: the "Context" section provided background information about the plot (such as characters, location, and time; see example SF), while the "Action" section described the supernatural events (for instance, *Harry pushed his trolley, rushed towards the wall, and passed through it*). The word count for the three scenario types was controlled, with the average word count of the "Context" section being 114.64 (range=106–123), 114.47 (range=105–123), and 114.52 (range=105–123), and the "Action" section being 42.86 (range=30–51), 42.67 (range=31–51), and 42.67 (range=31–51) for SF, SR, and RR, respectively. To illustrate the experimental conditions, an example scenario is provided below:

SF: supernatural scenarios with fictional characters

Context: 新学期终于开始了, 哈利满怀激情来到火车站, 却找不到自己列车的站台在哪里, 他问旁边的乘务员, 乘务员指了指对面, 他走过去, 发现那里什么也没有。有一个陌生女人看见了他, 好心地跟他说: “你只要照直朝第九和第十站台之间的隔墙走就是, 别停下来。” (*The new school year finally began. Harry came to the train station full of excitement but could not find the platform of his train. He asked the guard next to him, and the guard pointed to the opposite side. He walked over and found that there was nothing there. A woman noticed him and said kindly, "All you have to do is walk straight at the barrier between platforms nine and ten. Don't stop."*)

Action: 哈利这时推着行李箱向墙冲去, 果然就穿过了这堵墙, 进入了站台里面。

(*Harry then pushed his trolley and rushed towards the wall, and sure enough, he passed through it and reached the platform.*)

SR: supernatural scenarios with realistic characters

Context: 新学期终于开始了, 钟星满怀激情来到火车站, 却找不到自己列车的站台在哪里, 他问旁边的乘务员, 乘务员指了指对面, 他走过去, 发现那里什么也没有。有一个陌生女人看见了他, 好心地

跟他说: “你只要照直朝第九和第十站台之间的隔墙走就是, 别停下来。”

(*The new school year finally began. Zhong Xing came to the train station full of excitement but could not find the platform of his train. He asked the guard next to him, and the guard pointed to the opposite side. He walked over and found that there was nothing there. A woman noticed him and said kindly, "All you have to do is walk straight at the barrier between platforms nine and ten. Don't stop."*)

Action: 钟星这时推着行李箱向墙冲去, 果然就穿过了这堵墙, 进入了站台里面。

(*Zhong Xing then pushed his trolley and rushed towards the wall, and sure enough, he passed through it and reached the platform.*)

RR: realistic scenarios with realistic characters

Context: 新学期终于开始了, 钟星满怀激情来到火车站, 却找不到自己列车的站台在哪里, 他问旁边的乘务员, 乘务员指了指对面, 他走过去, 发现那里什么也没有。有一个陌生女人看见了他, 好心地跟他说: “你只要照直朝第九和第十站台之间的隔墙走就是, 别停下来。”

(*The new school year finally began. Zhong Xing came to the train station full of excitement but could not find the platform of his train. He asked the guard next to him, and the guard pointed to the opposite side. He walked over and found that there was nothing there. A woman noticed him and said kindly, "All you have to do is walk straight at the barrier between platforms nine and ten. Don't stop."*)

Action: 钟星这时推着行李箱向前走去, 果然就找到了那站台, 进入了列车里面。

(*Zhong Xing then pushed his trolley and walked along the wall, and sure enough, he found it and reached the carriage.*)

Norming tests

We employed linear mixed-effects models (LMMs) in R (version 4.2.1, 2022) to analyze the norming tests. The LMMs were constructed using the lmerTest package in R (version 4.0.2, R Development Core Team, 2020), with the dependent variable being the norming test scores. The models were compared and simplified stepwise. We employed the anova() function in R to compare models. For significant main effects, we conducted multiple pairwise comparisons using the EMMEANS() function. False Discovery Rate (FDR) correction for multiple comparisons was applied when decomposing significant models with the EMMEANS function.

A supernaturalness rating was conducted to determine the level of supernaturalness of these crucial items. Thirty-eight participants who did not take part in the formal experiment were asked to rate the supernaturalness of each scenario on a 5-point Likert scale (with 1 being the least supernatural and 5 being the most supernatural). They were randomly assigned to one of three counterbalanced lists, ensuring that they only viewed one condition per item. The Linear Mixed Model (LMM) analysis conducted on the supernaturalness ratings revealed a significant main effect of Scenario Type ($\chi^2 = 222.95$, $df = 2$, $p < 0.001$). After decomposing the main effect using emmeans with correction, we found that SF was rated as more supernatural than RR ($\beta = 1.369$, $t(767) = 13.993$, $p_{FDR} < 0.001$), as seen in Fig. 1a. Additionally, the rating of SR was also significantly higher than RR ($\beta = 1.363$, $t(767) = 13.905$, $p_{FDR} < 0.001$). However, there was no difference between SF and SR ($\beta = 0.006$, $t(767) = .062$, $p_{FDR} = 0.951$).

An acceptability test was conducted to determine the level of acceptability for each scenario. Another 46 participants were then asked to rate the acceptability of each scenario on a 5-point Likert scale (with 1 being the least acceptable and 5 the most acceptable). The LMM analysis revealed a marginal significant main effect of Scenario Type ($\chi^2 = 5.411$, $df = 2$, $p = 0.067$). Further analysis, as depicted in Fig. 1b, revealed that participants rated SF higher than SR (with marginal significance; $\beta = 0.134$, $t(1247) = 2.306$, $p_{FDR} = 0.055$). Nevertheless, no differences were found in the other comparisons ($ps > 0.05$), implying that supernatural actions carried out by fictional characters were perceived as more acceptable.

Twenty filler scenarios were created to prevent participants from using specific strategies to process the material. These scenarios were created to

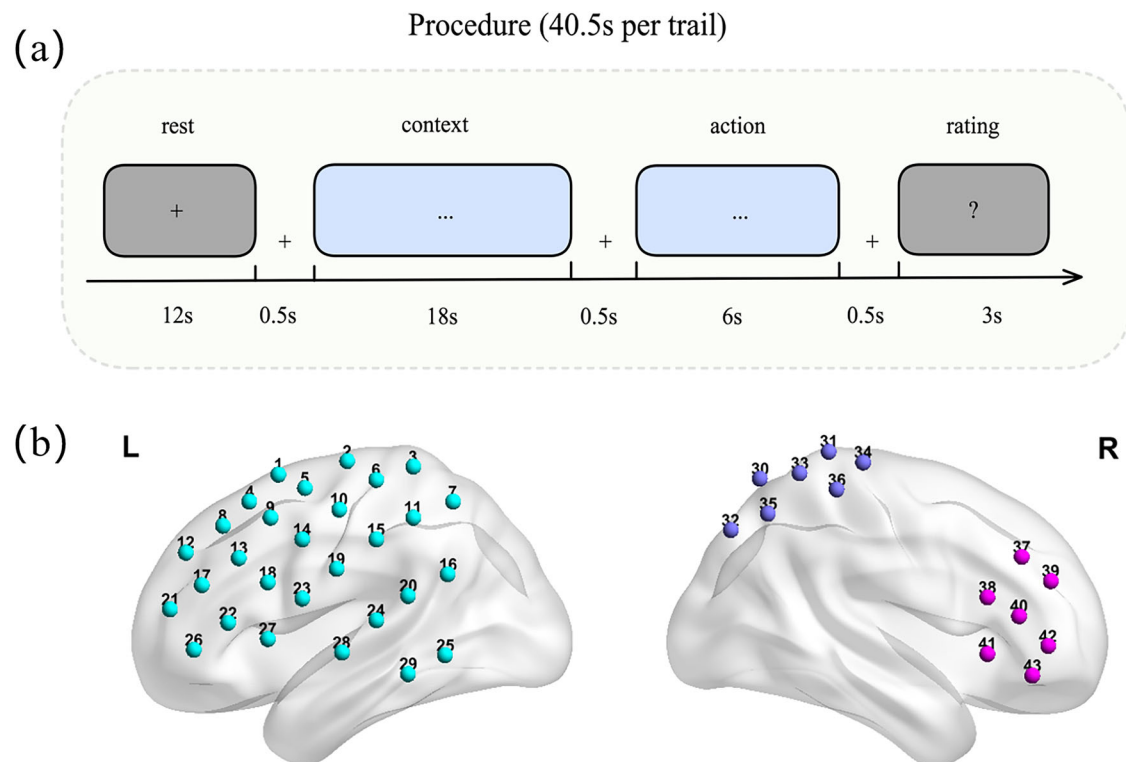


Fig. 4 | Experimental procedure and Channel distribution. a Flow chart of stimuli presentation. **b** Channel distribution over both hemispheres. The location of the brain region is collected by a 3D positioning device and projected onto the surface of the brain through NIRS-SPM fitting.

have similar sentence structures and lengths as the experimental scenarios. Derived from Philip Pullman's fantasy novel, *His Dark Materials* trilogy, these scenarios consisted of ten supernatural and ten unsupernatural scenarios. To ensure their alignment with the crucial elements of the material, the characters in the novel were partially replaced with supernatural names (e.g., *Harry Potter*) and realistic names. Twenty comprehension questions were formulated for the filler scenarios to assess the participants' comprehension of the complete scenarios (but the experimental scenarios were not included in this evaluation). A total of 62 scenarios were organized using a Latin square procedure, mixing the filler and experimental scenarios at random. Participants were randomly assigned to one of three counter-balanced experimental lists. The order of the scenarios was pseudo-randomized to ensure that no more than three consecutive scenarios were of the same condition, and that no more than three consecutive scenarios had probing questions with the same intended answer (i.e., TRUE/FALSE).

Procedure

Participants were seated in front of a computer screen and instructed to carefully read each scenario. Each trial began with a fixation cross for 500 ms, and followed by a blank screen for 12,500 (including the 500 ms fixation). The "Context" section was then presented for 18,000 ms, followed by a 500 ms fixation and then the "Action" section for 6000 ms. Another 500 ms fixation was presented, followed by a question mark in the middle of the screen for 3000 ms (see Fig. 4a). Participants were instructed to rate each scenario on a 5-point Likert scale of supernaturalness, ranging from "1" (very non-supernatural) to "5" (very supernatural). Each trial lasted 40.5 s in total. Each participant wore a special cap with 31 fNIRS optodes to measure their hemodynamic responses to the stimuli and completed the localization of all optodes after the practice part (see Fig. 4b). The formal experiment lasted approximately 45 min.

Upon completion of fNIRS data collection, participants were instructed to complete the Autism Spectrum Quotient (AQ) Questionnaire. This questionnaire was employed to evaluate individual differences in social skills, communication, imagination, attention switching, and attention to

detail. The AQ is a concise self-administered tool developed by Baron-Cohen and colleagues that aims to assess the extent to which adults with average intelligence exhibit traits commonly associated with the autism spectrum (with low social cognition ability)⁴⁴. It is widely used to identify individuals in the general population who may display autism-related characteristics or possess high levels of autistic traits⁴⁵. Given that our research focuses on how readers recognize and immerse themselves in fictional stories, the AQ can provide information about an individual's ability to process atypical social interactions, which is particularly important for understanding how readers relate to characters in fictional worlds. The questionnaire consisted of 50 questions, with ten questions allocated to each of the five aspects. It is worth noting that a higher score (ranging from 1 to 10) in the AQ indicates a greater likelihood of poorer performance in a specific aspect (the increased likelihood of autism).

fNIRS recording

The experimental procedure was prepared and presented using E-prime 3.0. Hemodynamic data were collected utilizing an fNIRS system (LAB-NIRS, Shimadzu Corporation). The signal acquisition had a temporal resolution of 99 ms, resulting in a sample rate of 10.101 Hz. Figure 4b provides a visual representation of the placement of the optodes, with 43 channels distributed across both hemispheres for each participant. The design involved three panels consisting of 16 transmitters (T) and 15 receivers (R), effectively covering most brain areas in the left hemisphere, right parietal areas (SPG, AG, poCG), and frontal area (IFG, MFG) (based on the international 10–20 system). Each transmitter emitted three wavelengths of light (780 nm, 805 nm, and 830 nm), and each receiver measured the absorbance for each of these wavelengths. Four referential head landmarks, including nasion (Nz), top center (Cz), left (AL), and right tragi (AR), were recorded using a Patriot 3D Digitizer (Polhemus, Colchester, VT) to calculate the MNI coordinates and corresponding brain areas with the NIRS-SPM toolbox⁴⁶ in MATLAB_R2020b (Mathworks, Natick, MA). The estimated anatomical locations of each channel are presented in Supplementary Table 1.

Data analysis

We first conducted fNIRS data preprocessing to obtain the intensity of the hemodynamic response to all stimuli in each trial. We then performed activation analysis using beta values extracted from the preprocessing step to identify potential brain regions involved in comprehending supernatural/realistic scenarios. To further examine the influence of individual differences in social cognition on brain activation, we carried out mediation analysis. Finally, to explore how the activated regions interact to support supernatural reading, we conducted functional connectivity analysis using the Phase Locking Value (PLV).

fNIRS data preprocessing

The fNIRS data selected for formal analysis includes both the “Context” section and the “Action” section. Preprocessing and first-level analysis of fNIRS data were conducted using the Homer3 toolbox in MATLAB_R2020b (Mathworks, Natick, MA)⁴⁷. After evaluating the data from all channels, an optical density data conversion was performed, converting the original light intensity data into optical density (OD) data. Subsequently, a wavelet motion correction procedure was applied to correct for motion artifacts in the optical density data⁴⁸. The data was then filtered using a bandpass filter with a range of 0.01 Hz to 0.1 Hz. Using the modified Beer–Lambert law, the optical density data were converted to concentrations of oxyhemoglobin (HbO) and deoxyhemoglobin (HbR). To further compensate for motion artifacts, a correlation-based signal improvement of the concentration changes was implemented. Finally, the baseline correction was calculated by subtracting the mean of the average values from the 5-second period preceding each scenario. Previous studies consistently demonstrate that changes in levels of oxyhemoglobin (HbO) reliably reflect regional cerebral blood flow, while variations in levels of deoxyhemoglobin (HbR) are influenced by changes in venous blood oxygenation and volume⁴⁹. We therefore chose to focus on the HbO concentration as the primary measure for assessing regional cerebral blood flow. Individual-level analyses were conducted using the NIRS-KIT toolbox in MATLAB⁵⁰, specifically estimating the general linear model (GLM) for the hemodynamic activity of HbO signals for each participant. To derive the beta values, which represent the intensity of the hemodynamic response to all stimuli in each trial, the design matrix for each participant under each condition was convolved separately with a hemodynamic response function. Finally, the beta values were transformed into Z-scores.

Activation analysis

We employed linear mixed-effects models (LMMs) in R (version 4.2.1, 2022) to analyze patterns of hemoglobin signal activation across participants while reading different scenarios⁵¹. The LMMs were constructed using the lmerTest package in R (version 4.0.2, R Development Core Team, 2020), with the dependent variable being the hemodynamic signal evoked under each experimental condition. Separate LMMs were built for each channel. To control for Type I errors due to multiple comparisons, we applied a comprehensive False Discovery Rate (FDR) correction to 43 channels using the p.adjust function in R (method = “fdr”). Both the raw and corrected p-values are provided (see Table 1). When discussing significant results in the text, we exclusively refer to findings that remain significant after FDR correction. Each model included *Scenario Type* (SF, SR, and RR) and *HP familiarity* (high vs. low) as fixed effects, along with their interaction. The models also had a maximal random effects structure, with random intercepts for participants and items, and included the interaction term as a by-participant and by-item random slope. The models were compared and simplified stepwise. The final models retained the fixed interaction effects of *Scenario Type* and *HP familiarity* and a random intercept for items. For channels showing significant main or interaction effects, we conducted multiple pairwise comparisons using the EMMEANS() function. FDR correction for multiple comparisons was applied when decomposing significant models with the EMMEANS function.

Additionally, to examine how brain activations were modulated by the online supernaturalness judgments, we carried out correlation analyses

between the online supernaturalness ratings and brain activations in the channels that showed significant effects in the group-level analysis.

Mediation analysis

To explore the possible influence of individual variations in social cognition on the connection between supernaturalness and participants’ brain activity, we used participants’ ratings of supernaturalness during the fNIRS experiment as the independent variable. The dependent variable was the brain activity in specific channels identified during the comparison of SR to RR and SR to SF. We then employed a Multi-level Modeling (MLM) to assess the mediating role of individual differences in AQ by examining its potential influence on the relationship between the independent and dependent variables. In the model, random intercepts were included to capture between-subject variability. Given our focus on the role of social cognition in supernatural reading, we averaged the scores from three AQ subscales directly related to social cognition: social skills, communication, and imagination (S-C-I). Additionally, we also tested the mediating role of each of these three subscales individually in supernatural reading.

Functional connectivity analysis

Functional connectivity analysis was performed using MATLAB (R2020b). Initially, functional connectivity (FC) was calculated exclusively for the HbO signal after preprocessing, as previous studies have demonstrated its superior signal-to-noise ratio⁵². The Phase Locking Value (PLV) was then computed for all possible channel pairs, resulting in a CH×CH matrix (43×43 channel pairs) that represented the strength of functional connectivity between each pair of channels for each participant. Subsequently, group-level PLV values were obtained based on the HP level of each participant, reflecting functional connectivity between identical channel pairs across different conditions. To determine the statistical significance of the differences in PLV, one-tailed *t* tests were conducted to compare the PLV across the three main contrasts (i.e., SF > RR, SR > SF, SR > RR) for each participant, as well as between these contrasts within high- and low-familiarity levels. The resulting p-values were corrected for multiple comparisons using the False Discovery Rate (FDR) method across all recorded channels.

Data availability

The behavioral and fNIRS data used in this study are available at Open Science Framework (<https://osf.io/y2pqe/>).

Code availability

The underlying codes for this study are available on request by contacting the corresponding author.

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Conceptualization: X.X., K.C., L.C. Methodology: X.X., K.C. Formal analysis: C.J. Visualization: C.J. Supervision: X.X., L.C. Writing—original draft: X.X., K.C., L.C. Writing—review & editing: X.X., L.C., C.J. All authors have read and approved the paper.

Competing interests

The authors declare no competing interests.

Additional information

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