

Neural Correlates of Analogical Reasoning on Syntactic Patterns

Zhongshan Li^{1*}, Zhuqian Zhou^{2*}, Xiaoling Wang¹, Jinshan Wu¹, and Luyao Chen^{1,3}

Abstract

■ Analogical reasoning is central to thought and learning. However, previous neuroscience studies have focused mainly on neural substrates for visuospatial and semantic analogies. There has not yet been research on the neural correlates of analogical reasoning on syntactic patterns generated by the syntactic rules, a key feature of human language faculty. The present investigation took an initial step to address this paucity. Twenty-four participants, whose brain activity was monitored by fMRI, engaged in first-order and second-order relational judgments of syntactic patterns as well as simple and complex working memory tasks. After scanning, participants rated the difficulty of each step during analogical reasoning; these ratings were related to signal intensities in activated regions of interest using Spearman correlation analyses. After prior research, differences in

activation levels during second-order and first-order relational judgments were taken as evidence of analogical reasoning. These analyses showed that analogical reasoning on syntactic patterns recruited brain regions consistent with those supporting visuospatial and semantic analogies, including the anterior and posterior parts of the left middle frontal gyrus, anatomically corresponding to the left rostrolateral pFC and the left dorsolateral pFC. The correlation results further revealed that the posterior middle frontal gyrus might be involved in analogical access and mapping with syntactic patterns. Our study is the first to investigate the process of analogical reasoning on syntactic patterns at the neurobiological level and provide evidence of the specific functional roles of related regions during subprocesses of analogical reasoning. ■

INTRODUCTION

Analogical reasoning is central to thought and learning (Hofstadter & Sander, 2013; Namy & Gentner, 2002; Gentner & Holyoak, 1997; Holyoak, Thagard, & Sutherland, 1995). Defined as the ability to perceive and use relational similarity between two situations or events (Gentner & Smith, 2012), analogical reasoning encompasses problem solving, relational mapping, and representation in general and depends on the ability to consider and compare relationships and integrate or match those relationships (Hobeika, Diard-Detoef, Garcin, Levy, & Volle, 2016; French, 2002; Goswami, 1991). Across diverse fields, analogical reasoning is employed to understand new concepts or novel information (Dunbar & Blanchette, 2001), to solve practical problems (Gick & Holyoak, 1980, 1983), and to facilitate the learning of new content in educational settings (Gray & Holyoak, 2021; Vendetti, Matlen, Richland, & Bunge, 2015; Richland & McDonough, 2010; Richland, Zur, & Holyoak, 2007).

Because of this importance, there have been a myriad of neuroimaging studies investigating the neurobiological bases of analogical reasoning. One particularly useful approach to understanding the mechanisms of analogical reasoning is to examine four-term analogies in the classic

form of A is to B as C is to D, denoted as $A:B::C:D$, such as sky is to bird as ocean is to fish (denoted as $sky:bird::ocean:fish$) and blizzard is to snowflake as army is to soldier ($blizzard:snowflake::army:soldier$). This form is widely used because it simplifies analogical reasoning by decomposing the process of analogy into constituent processes (Gentner, 2003; Grudin, 1980; Spearman, 1923). Studies adopting the $A:B::C:D$ paradigm have used it to examine major subtypes of analogy, including semantic analogy tasks (Reber, Luechinger, Boesiger, & Henke, 2014; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010, 2012; Wendelken, Chung, & Bunge, 2012; Wendelken, Nakhabenko, Donohue, Carter, & Bunge, 2008; Bunge, Wendelken, Badre, & Wagner, 2005; Luo et al., 2003) and visuospatial analogy tasks (Aichelburg et al., 2016; Watson & Chatterjee, 2012; Wendelken et al., 2012; Preusse, Elke, Deshpande, Krueger, & Wartenburger, 2011; Cho et al., 2010; Geake & Hansen, 2005, 2010; Volle, Gilbert, Benoit, & Burgess, 2010; Wartenburger, Heekeren, Preusse, Kramer, & Van der Meer, 2009; Christoff, Ream, Geddes, & Gabrieli, 2003). Previous findings have suggested that the most anterior, left lateral region of the pFC, also called the anterior pFC, frontopolar cortex, or rostrolateral pFC (rlPFC), is critical to analogical reasoning. This area corresponds roughly to Brodmann's area 10 (Parsons & Davies, 2022; Green et al., 2017; Hobeika et al., 2016; Urbanski et al., 2016; Krawczyk et al., 2008; Morrison

¹Beijing Normal University, ²Columbia University, ³Max Planck Institute for Human Cognitive and Brain Sciences

*Contributed equally and considered co-first authors.

et al., 2004; Christoff et al., 2001). The common brain area activated for analogical reasoning across the two task domains is the left rPFC, although the region recruited by semantic tasks is located more ventrally than that recruited by visuospatial tasks (Wendelken et al., 2012). These findings implicate the left rPFC as the locus supporting the process of abstraction from concrete, domain-specific details to the general principles and rules that enable higher-level cognition (Wendelken et al., 2012). In conjunction with this role of the left rPFC as the primary shared region for analogical reasoning, specialization for semantic and visuospatial analogy tasks was mainly observed in the inferior and middle frontal gyri, respectively (Hobeika et al., 2016).

Nevertheless, analogical reasoning employing visuospatial or semantic patterns does not represent the full extent of analogical reasoning. This omits a significant form of analogical reasoning—the one involving syntactic patterns generated by syntactic rules (i.e., “syntactic analogy” in this study). Syntactic patterns are interconnected with, yet distinct from, both semantic and visuospatial patterns. On the one hand, although syntax and semantics are both language related, syntax could abstract from the relatively concrete conceptual–semantic relations directly referring to the objective world to the semantics-free combinatorial rules, and the use of these syntactic combinatorial rules is the basic way of human cognition to understand the world (e.g., Berwick, Friederici, Chomsky, & Bolhuis, 2013; Chang, Dell, & Bock, 2006). On the other hand, syntactic and visuospatial patterns, although not mutually exclusive, focus on different aspects of stimuli in the cognitive task. When a syntactic pattern is visually presented, it is not problematic to also classify it as a visuospatial pattern (Tettamanti et al., 2013; Greenfield, 1991). However, the essence of a syntactic pattern resides in relations among its parts rather than in its visual attributes (Goldwater, 2017). The same syntactic pattern can be depicted in various modes, including visual, auditory, or tactile (Conway & Christiansen, 2005), whereas attributes essential for the investigation of visuospatial processing, such as color (Eimer & Kiss, 2008; Rösler, Heil, & Hennighausen, 1995), shape (Wendelken et al., 2012; Roser, Fiser, Aslin, & Gazzaniga, 2011), and orientation (Medina et al., 2009; Tversky, 2005), are exclusively confined to the visual mode. Moreover, when visuospatial patterns do concern relations, they often remain nonsyntactical. For instance, the Raven Progressive Matrices tests (Raven, 2003, 1938) represent a common type of visuospatial tasks employed in studies of relational processing and analogical reasoning. However, the tests are nonsyntactical not only because they lack an overt connection to language but also because focal relations in the tests pertain to relations that are between-item (Crone et al., 2009; Christoff et al., 2001), as opposed to within-item. The latter–within-item relations and patterns, however, are integral to syntax because they determine grammaticality in the item, be it a figure or a string. Given such connections and

distinctions, it is intriguing to explore whether syntactic analogy shares a common neural basis with the visuospatial analogy when the symbols are presented in the visual domain.

Apart from their differences from visuospatial and semantic patterns, syntactic patterns warrant separate neuroscience research in analogical reasoning also because of its defining role in human language (e.g., Friederici, 2017; Berwick et al., 2013; Hauser, Chomsky, & Fitch, 2002). Syntactic rules and their generated patterns constitute the basis of the language system (Berwick et al., 2013), underpin the human language faculty (Hauser et al., 2002), and play a vital role in language acquisition (Gómez & Gerken, 2000). Both generativist–nativist accounts (e.g., Wexler, 1998) and usage-based constructivist accounts (e.g., Tomasello, 2003) propose stored abstractions (e.g., a “give sb a + X” slot-and-frame pattern of the ditransitive construction) in terms of syntactic representations in the human brain. However, the so-called stored abstractions are not necessarily represented in forms of explicit rules (Ambridge, 2020a, 2020b). Rather, Kuehne, Gentner, and Forbus (2000) have demonstrated via simulations that rule-like behaviors in grammar learning can emerge without explicit knowledge of syntactic rules. An explanation of how human beings develop syntactic competence without explicit instruction or deliberate abstraction of syntactic rules is based on analogical reasoning (Ambridge, 2020a, 2020b; Gentner & Hoyos, 2017; Goldwater, 2017; Vokey & Higham, 2005; Tomasello, 2000; Brooks & Vokey, 1991). Tomasello (2000) described the beginning of syntactic development as processes of structure combination and analogy formation where kids form abstract utterance-level constructions by creating analogies among utterances emanating from different item-based constructions. Vokey and Higham (2005) further showed that even adults relied on analogies to assess the grammaticality of test items in artificial grammar learning, as opposed to abstracting rules. Although it is still an ongoing debate whether the syntactic behavior of human beings can be explained solely by analogical reasoning (Adger, 2020; Ambridge, 2020a, 2020b; Lieven, Ferry, Theakston, & Twomey, 2020), we are inclined to adopt a moderate stance, akin to Goldwater’s (2017), in recognizing the importance of analogical reasoning in syntax learning and processing, while refraining from making a definitive judgment regarding its exclusive role as the sole supporting mechanism. Given analogical reasoning is crucial for scaffolding the formation of syntactic patterns and syntactic rule acquisition, the absence of knowledge regarding the localized brain regions and neural correlates of analogical reasoning on syntactic patterns is concerning.

Therefore, the primary goal of this study was to delineate the neural substrates for analogical reasoning on syntactic patterns generated by syntactic rules. At this initial stage, we particularly focused on exploring the boundary between syntactic analogies in the visual modality (as teachers would write down the syntactic patterns on the

board in school language education) and the other visually presented analogies—visuospatial and semantic—than on syntactic processing per se. This is to say, whether analogical reasoning on the visually presented syntactic patterns would be plainly explained by the neural substrates of visuospatial (or semantic) analogy or any neural correlates specific to syntactic analogy. To this end, we integrated the four-term analogy paradigm (A:B::C:D) with the Chomsky hierarchy-driven paradigm of artificial grammar processing (Chomsky, 1956), building upon the design by Wendelken et al. (2012) where the neural substrates for the latter two types of analogies were thoroughly investigated (see Figure 1).

Four-letter strings in the forms of AABB, ABBA, ABAB, and their reverse patterns were used in the present study. They were generated by syntactic rules corresponding to three common classes of supra-regular grammars in the Chomsky hierarchy. We chose to develop our experimental material based on this classic form of artificial grammar because it is theoretically grounded (Linz & Rodger, 2022; Jäger & Rogers, 2012; Levelt, 2008; Hopcroft, Motwani, & Ullman, 2001; Chomsky, 1956), widely used as a model system for studying syntax (see Fitch & Friederici, 2012, and Uddén & Männel, 2018, for comprehensive reviews), and well suited for a range of populations from adults to infants and even to animals (ten Cate, Gervain, Levelt, Petkov, & Zuidema, 2020; ten Cate & Okanoya, 2012; Folia, Uddén, De Vries, Forkstam, & Petersson, 2010; Reber, 1967). It is also noteworthy that a visual pattern is not necessary in the form of a syntactic pattern generated by the (artificial) syntactic rules as already mentioned, whereas when such a visual pattern is constructed as a syntactic pattern, syntactic regions might be involved to parse it (see also Bahlmann, Schubotz, Mueller, Koester, & Friederici, 2009). Hence, it is critical to understand the neural substrates

underlying analogical reasoning on syntactic patterns, especially in the visual modality. Beyond the context of artificial grammar, the letter-string format stands out as one of the most straightforward analogical problem formats, facilitating precise manipulation and identification of valid analogies (Rull, Contreras, Córdoba, & Valenzuela, 2010). It also promotes relational mappings owing to its intricate internal structure (Burns, 1996). In short, we consider that letter-string analogy problems, despite their artificiality, serve as a robust cornerstone for the research into syntactic analogy.

With respect to the use of four-term analogy, the analogy tasks performed by participants involved both first-order (e.g., A:B::C:D) and second-order (e.g., A₁:B₁::C₁:D₁ vs. A₂:B₂::C₂:D₂) relational judgments (see Figure 1). Analogical reasoning is required in second-order relational judgments, and the brain areas involved in such reasoning were identified according to differences in activation in response to the second-order and first-order tasks by calculating the following contrast: second-order > first-order. As shown in Figure 1, analogical reasoning on syntactic patterns was designed similarly to the multiorder analogy in the visuospatial and semantic domains. In addition to the second-order > first-order contrast, a working memory task was also used to mask activation not associated with analogical reasoning, especially the difference in complexity between the second-order and first-order relational judgments. The relationships between the brain signals of the activated ROIs and the difficulty ratings of each step of analogical reasoning were also investigated to evaluate the functional roles of these ROIs. By specifying the brain regions recruited during syntax-related analogical processes, we expected to determine the similarities and differences during the performance of different analogical reasoning tasks, namely, syntactic analogical reasoning (in the present study) and visuospatial and semantic

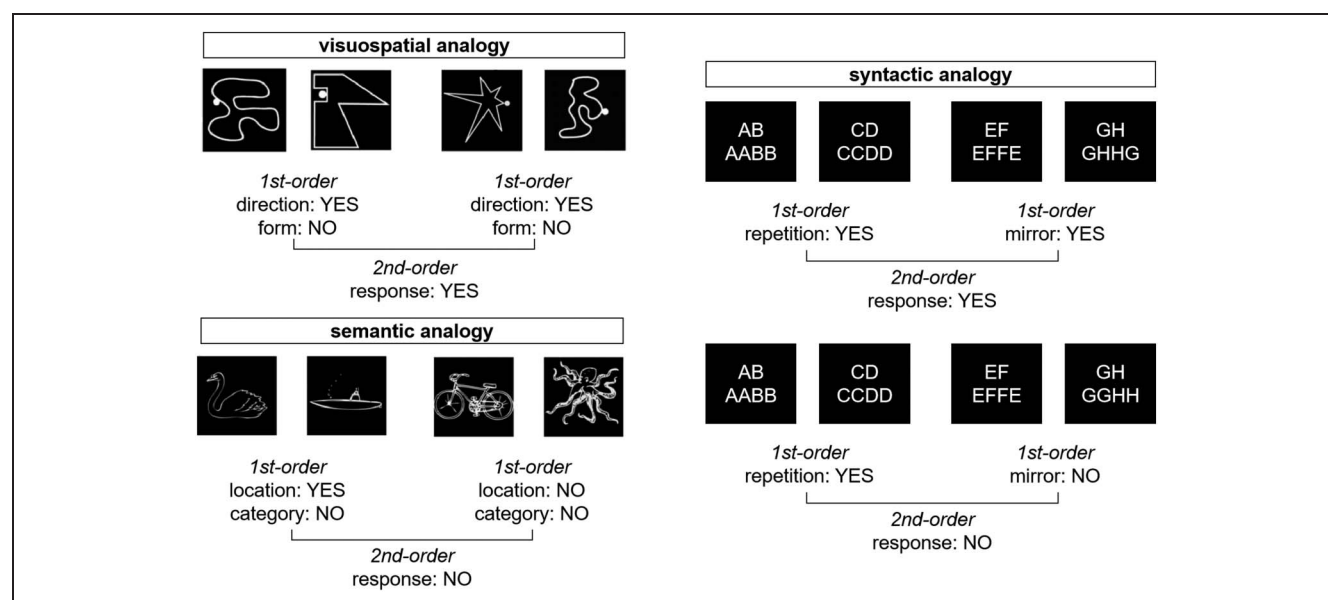


Figure 1. First- and second-order analogical reasoning for visuospatial, semantic (left; adapted from Wendelken et al., 2012), and syntactic domains.

analogical reasoning (in previous studies). Moreover, it remains unclear which subprocess of analogical reasoning is most strongly supported by the rLPFC. Generally, the rLPFC is speculated to be the brain region supporting analogy mapping given its role in reflective transfer (Anderson & Fincham, 2014) and relational integration (Christoff, Keramatian, Gordon, Smith, & Mädlar, 2009; Green, Fugelsang, Kraemer, Shamos, & Dunbar, 2006; Waltz et al., 1999). Nonetheless, Krawczyk, McClelland, Donovan, Tillman, and Maguire (2010) and Volle et al. (2010) both found that the rLPFC was more active during the encoding phase than during the mapping phase; Davis, Goldwater, & Giron, (2017), otherwise, noticed that rLPFC was highly active when learning a new relation for solving the problem but would not stay active if relations involved in subsequent problems remained unchanged. Therefore, we also sought to elucidate the role of the left rLPFC in specific analogical reasoning subprocesses related to syntactic patterns. These findings may shed light on the neurobiological mechanisms that underlie analogical reasoning on syntactic patterns and thus substantially expand our understanding of the neural basis of higher cognitive functions in humans.

METHODS

Participants

Twenty-four healthy young adults (12 women, 12 men; age: $M = 23.5$ years, $SD = 1.7$ years) from Beijing Normal University participated in the present fMRI experiment after providing informed consent. The sample size is comparable to previous similar studies of neural correlates of visuospatial and semantic analogical reasoning by Wendelken et al. (2012). All participants were right-handed as confirmed by the Edinburgh Handedness Inventory (Oldfield, 1971), had normal or corrected-to-normal vision, and were free of neurological disorders. They had no experience with Chinese Phonetic Alphabet letters (i.e., the Taiwanese Bopomofo, also called Zhuyin) or Japanese Katakana, which were utilized as unfamiliar word-like symbols (i.e., pseudowords) in this study (see Materials). Informed consent was obtained in a manner approved by the ethics committee of Beijing Normal University, Beijing, China. Each of the participants received 120 Chinese yuan in remuneration for participation.

Materials

To test analogical reasoning on syntactic patterns, we designed the organization of symbols to follow the patterns illustrated in Table 1, which, as was already mentioned in the Introduction, were generated by syntactic rules corresponding to three common classes of suprarregular grammars in the task blocks: regular repetition grammar (e.g., AABB), context-free mirror grammar (e.g., ABBA), and mildly context-sensitive copy grammar (e.g., ABAB; Jiang et al., 2018; Uddén & Männel, 2018;

Table 1. Syntactic Rules and the Corresponding Patterns Used in the Study

Types	Elements	Canonical Patterns	Reversed Patterns
Repetition	AB	AABB	BBAA
Mirror	AB	ABBA	BAAB
Copy	AB	ABAB	BABA
Uniform	AA	AAAA	AAAA

Uddén, Ingvar, Hagoort, & Petersson, 2017) according to the formal language theory hierarchy (Chomsky, 1956). We also designed one uniform pattern for the working memory task. Moreover, given that word order is not considered a fundamental feature of human syntax (Berwick et al., 2013), reversed patterns were also created, as shown in Table 1. In total, six string patterns were used in the analogical reasoning tasks, and a simple identical pattern was used in the working memory tasks.

Note that the As and Bs shown in Table 1 were replaced with pseudowords in the actual experiment. As mentioned above, the symbols used in the experiment were designed to exclude semantic information to focus on syntactic analogy. Our pseudoword clusters were composed of 24 Chinese Phonetic Alphabet letters and Chinese-character-like Japanese Katakana characters (i.e., ㄅ ㄆ ㄇ ㄏ). The 24 symbols were randomly and evenly divided into four groups of six, A, B, C, and D, corresponding to the A–B–C–D elements in a four-term analogy (e.g., AB:AABB::CD:CCDD). Hence, there were 7776 (= 6 left-hand-side [LHS] string patterns × 1 right-hand-side string pattern that is the same as the LHS pattern × 64 symbol combinations) unique, correct four-term analogies and 38,880 (= 6 LHS string patterns × 5 right-hand-side string patterns that are different from the LHS patterns × 64 symbol combinations) unique, incorrect four-term analogies possible for analogical reasoning tasks under our design. Analogies used in task trials were chosen from this large possibility space with no repeating analogies in each task.

All participants were unfamiliar with these symbols. Hence, participants could only rely on abstract syntactic patterns to process the possible relations with potential semantic interference eliminated (see also Uddén & Männel, 2018).

Tasks

Analogical Reasoning Tasks on Syntactic Patterns

In the first-order relational judgment trials, participants were asked to judge (following the A:B::C:D paradigm) whether the pair of elements that appeared on the second screen was an appropriate analogy of the pair on the first

screen. The 72 trials in the first-order task consisted of 36 correct four-term analogies (e.g., ㄅㄆ:ㄅㄆㄆㄆ::ㄆㄆ:ㄆㄆㄆ) and 36 incorrect four-term analogies (e.g., ㄅㄆ:ㄅㄆㄆㄆ::ㄆㄆ:ㄆㄆㄆㄆ). They were randomly ordered in the task trials.

The second-order task was composed of two first-order relations and required a second-order relational judgment based on the consistency of the two first-order relations, as previously designed by Wendelken et al. (2012). The second-order task trials were double the length of the first-order trials, as each trial contained four screens filled with pseudoword clusters. The second-order task consisted of 36 trials, namely, 18 correct analogies and 18 incorrect analogies, each containing an eight-term pattern concatenating two first-order four-term items. They were randomly ordered in the task trials. The eight-term second-order analogy was correct if the two first-order relationships were both correct (e.g., ㄅㄆ:ㄅㄆㄆㄆ::ㄆㄆ:ㄆㄆㄆㄆ vs. ㄅㄆ:ㄅㄆㄆㄆ::ㄆㄆ:ㄆㄆㄆㄆ) or both incorrect (e.g., ㄅㄆ:ㄅㄆㄆㄆ::ㄆㄆ:ㄆㄆㄆㄆ vs. ㄅㄆ:ㄅㄆㄆㄆ::ㄆㄆ:ㄆㄆㄆㄆ). The second-order analogy was incorrect if one of the two first-order relations was correct and the other was incorrect; that is, the relationship between the two first-order relations was inconsistent.

Working Memory Tasks

The working memory tasks required participants to recollect specific details about different patterns of pseudoword clusters from different screens and included two conditions: the simple working memory task (with only two screens) and the complex working memory task (involving four screens).

The simple working memory task asked participants to judge whether two screens in the same trial were identical. Each trial began with the “*” symbols. There were 36 correct trials, in which an identical match of the uniform pattern of a single element was presented (e.g., ㄅㄅ:ㄅㄅㄅㄅ), and 36 incorrect trials, in which the items in A:B and C:D were not identical (e.g., ㄅㄅ:ㄅㄅㄅㄆ).

The complex-task condition imposed a greater working memory load by including four screens of pseudoword clusters. The complex-task condition consisted of 36 trials. An analogy was considered correct if the fourth pair of terms was identical to one of the first three pairs (e.g., ㄅㄅ:ㄅㄅㄅㄆ::ㄆㄆ:ㄆㄆㄆㄆ vs. ㄆㄆ:ㄆㄆㄆㄆ::ㄆㄆ:ㄆㄆㄆㄆ). Otherwise, the analogy was considered incorrect.

Experimental Procedures

Participants completed both four-term A:B::C:D analogical reasoning and working memory tasks and made evaluative judgments under one of the following conditions: (1) analogical reasoning with first-order relations, (2) analogical

reasoning with second-order relations, (3) simple working memory, and (4) complex working memory.

Participants were first trained to understand the procedure and requirements of the experiment. Then, before the fMRI scan, a behavioral adaptation practice session (48 trials in total) was conducted to familiarize participants with the paradigm. Participants completed 24 trials of analogical reasoning tasks on syntactic patterns and 24 trials of working memory tasks and reached an average accuracy of 90% in the practice session, which demonstrated their clear understanding of the experiment. The pseudoword clusters in both the training session and the practice session were completely different from the experimental materials used in the scanning session to avoid a potential memory effect because of material similarities.

For the fMRI scanning session, the presentation of the stimuli was performed using a blocked design with two runs. The first run contained nine blocks of the first-order relational judgment and the simple memory task, and the second run contained nine blocks of the second-order analogical reasoning task and the complex memory task. Within each run, the blocks were pseudorandomized. There were eight trials per block in the first run and four trials per block in the second run. This was designed to keep the block duration comparable between the two runs. The order of individual trials was also randomized for each block. Overall, it took 15 min to complete a whole run. The order of the two runs was counterbalanced across participants. To avoid the unnecessary switching cost between the first- and second-order analogy tasks, each task was set in one run respectively, and in between the two runs, a 10-min break was given to help the hemodynamic response return to baseline. Participants remained lying in the scanner during the break.

During scanning, the two-symbol element and the generated four-symbol syntactic pattern were displayed on the same screen against a black background in a vertical manner, as shown in Figure 2. The pseudoword cluster on the evaluation screen for first-order relational judgments and simple working memory tasks was displayed in cyan, whereas that on the screen for second-order analogical reasoning and complex working memory tasks was displayed in magenta. Two screens were used to present a four-term first-order relational judgment trial or a simple working memory task trial, and four screens were used to present an eight-term second-order analogical reasoning task trial or a complex working memory task trial.

The beginning of both the first-order and second-order analogical reasoning trials was denoted by a 500-msec fixation cross. There were two screens with pseudoword clusters in each trial for first-order relational judgment trials. For the second-order analogical reasoning, there were two first-order sequences within a trial separated by a screen displaying “#.” Each of the stimuli screens with clusters was presented for 2000 msec. A black screen separated the stimuli screens and appeared for 500 msec. Participants were required to make a judgment in 2500 msec

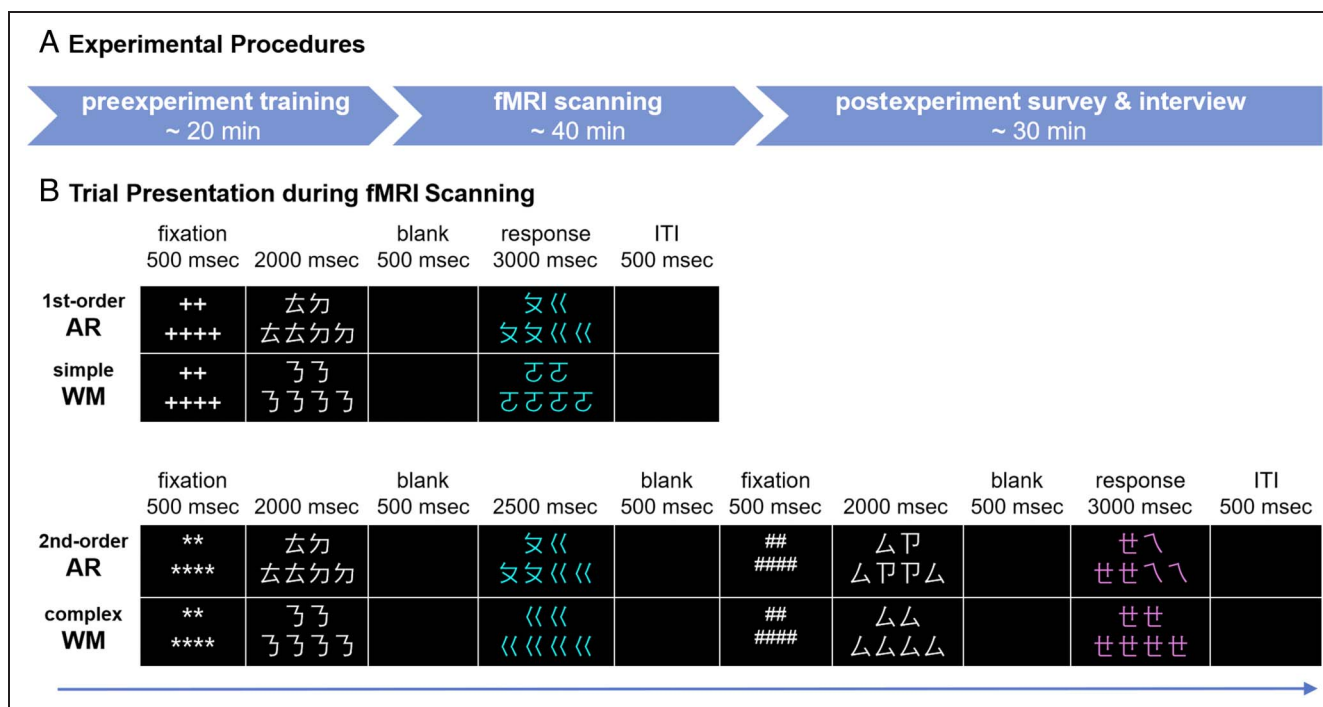


Figure 2. The procedures of the experiment. (A) The complete experimental procedures. First, participants underwent preexperimental training and practice to understand the rules and directions. Second, they underwent the fMRI scanning session. Finally, participants completed a survey and an interview. (B) fMRI scanning session included two runs: Run 1 with first-order relational judgment and simple working memory tasks; Run 2 with second-order relational judgment and complex working memory tasks. The presentation of the trials with the timing parameters was shown. See the main text for details. AR = analogical reasoning; ITI = intertrial interval; WM = working memory.

or within 3000 msec after the stimuli screens appeared. The intertrial interval was set to 500 msec. No feedback was provided.

Both the simple memory task and the complex memory task started with a 500-msec fixation on the screen displaying “*” symbols. Each trial consisted of two screens with pseudoword clusters in the simple memory task. Trials of the complex memory task consisted of four screens within a trial, with a screen displaying “#” symbols appearing between the second and third screens. Each of the stimuli screens with clusters was presented for 2000 msec. A black screen lasting 500 msec separated clusters. Participants were required to make a judgment in 2500 msec or within 3000 msec after the two screens appeared. If a judgment was entered, the intertrial interval was set to 500 msec. No feedback was provided. The experimental procedures are illustrated in Figure 2.

To further investigate which analogical subprocesses were the most difficult, we conducted a posttest survey to collect participants’ self-reported difficulty ratings of possible subprocesses (see Appendix A for a full list of subprocesses in the survey including distractors) involved in the first-order and second-order tasks; difficulty was rated on a Likert scale from 1 to 5. Participants rated a subprocess as “zero” if they did not use the subprocess in question (e.g., distractors). A semistructured posttest interview was also conducted to further investigate participants’ experiences during the task.

Imaging Data Acquisition

MRI data were acquired via a 3.0-T Trio magnetic resonance scanner (Siemens AG) with a 12-channel head coil at the State Key Laboratory of Cognitive Neuroscience and Learning of Beijing Normal University. A T2*-weighted gradient EPI sequence sensitive to BOLD signals was adopted with the following parameters for functional data acquisition: repetition time = 2000 msec, echo time = 30 msec, flip angle = 90°, field of view = 192 × 192 mm², base resolution = 64 × 64 mm², in-plane resolution = 3 × 3 mm², slice thickness = 1 mm, gap = 3 mm, and alignment to the AC–PC plane. High-resolution anatomical images (magnetization prepared rapid gradient echo) were acquired first from each participant, followed by the acquisition of echo-planar functional images during the performance of the tasks. Each volume consisted of tilted axial slices (1 mm thick, 3-mm slice gap) that provided coverage of almost the whole brain. Anatomical T1-weighted images were acquired in the following space: repetition time = 2530 msec, echo time = 3.39 msec, slice thickness = 1.33 mm, no slice gap, and flip angle = 90°. Head motion was limited using foam padding.

Imaging Data Preprocessing

Preprocessing was conducted using DPARSF 5.1 Advanced Edition (DPARSF: Data Processing Assistant for Resting-

State fMRI; Yan, Wang, Zuo, & Zang, 2016), implemented in MATLAB (MathWorks) R2020b. The preprocessing steps followed those of Yan et al. (2013), including (a) removing the first four volumes to reduce the magnetic saturation effect; (b) slice-timing correction; (c) field mapping; (d) spatial realignment; (e) coregistration; (f) segmentation (new segment + DARTEL); (g) nuisance covariate regression (polynomial trend: 1, linear detrending), including head motion regression with the Friston-24 model; (h) normalization of the images to the EPI template based on Montreal Neurological Institute (MNI) stereotactic space to minimize cerebral differences between participants and resampling the images into $3 \times 3 \times 3 \text{ mm}^3$; and (i) smoothing the images with a 3-D Gaussian kernel with an FWHM of 4 mm.

Data from two participants were excluded from the analyses because of excessive head motion ($>3 \text{ mm}$ in translation or $>3^\circ$ in rotation). Therefore, the fMRI data of 22 of the 24 participants were further processed and analyzed.

Whole-Brain Analyses

Whole-brain analyses were performed using SPM 12 (www.fil.ion.ucl.ac.uk/spm/) implemented in MATLAB R2020b. At the first level, a general linear model was constructed for each participant by adding the four conditions (i.e., first-order and second-order analogical reasoning tasks and the two working memory tasks) as four regressors of interest, with the onset and duration of each block modeled as a boxcar function, which was further convolved with a canonical hemodynamic response function. Subsequently, the data were high-pass filtered at 128 Hz to eliminate low-frequency drifts.

At the second level, following Wendelken et al. (2012), the paired-samples *T*-contrast of interest (second-order [relational judgments] $>$ first-order [relational judgments]) was performed. Moreover, we also performed the contrast of complex working memory $>$ simple working memory to evaluate to what extent the regions supporting analogical reasoning on syntactic patterns could be differentiated from regions supporting working memory. These regions served as the working memory mask for exclusively masking the activation results under the second order $>$ first order contrast to ensure that activation solely reflected the functional role of the related areas for analogical reasoning on syntactic patterns. Notably, following Yan et al. (2013), each individual's mean framewise displacement Jenkinson value was

included as a covariate to regress out the head motion artifacts. The second-level contrast results were thresholded at $p_{\text{uncorr}} < .0001$ and cluster size (K_E) ≥ 10 (voxel level), and only the regions with cluster-level $p_{\text{FWE}} < .05$ were reported as showing significant activation.

ROI Analyses

ROI analyses were performed using MarsBaR (Tzourio-Mazoyer et al., 2002). Functionally defined ROIs were obtained from the activated clusters identified in the whole-brain contrasts at the second level. For each ROI, a 4-mm-radius sphere was created, centered on the peak activation coordinates. The percent signal change (hereafter, signal intensity) was extracted from each ROI in the first- and second-order tasks, and its correlation with performance in the corresponding task was assessed via Spearman correlation analysis.

RESULTS

Behavioral Results

Accuracy, RTs, and the computed task performance metric for the two conditions are presented in Table 2. Task performance in this study was operationalized as $RT \times [1 + 2 \times (1 - \text{accuracy})]$, taking into consideration both the RT and accuracy (Lyons, Price, Vaessen, Blomert, & Ansari, 2014); the smaller the value was, the better the participants performed.

Paired-samples *t* tests were performed to compare participant performance among experimental conditions. There were significant differences in accuracy, $t(21) = -6.44$, $p < .001$, as well as in RTs, $t(21) = 10.57$, $p < .001$, between first-order and second-order analogical reasoning tasks. This finding showed that, as expected, the second-order task required more analogical reasoning effort than the first-order task.

According to the posttest survey, participants found analogical mapping (mapping the syntactic patterns on the two screens) to be the most difficult in both the first-order task ($M = 2.59$, $SD = 1.14$) and the second-order task ($M = 3.82$, $SD = 0.85$), which aligns with the analogical reasoning literature, in that mapping is the fundamental (Hummel & Holyoak, 2003; Gentner, 1983) and “expensive subprocess” (Parsons & Davies, 2022) of analogical reasoning (difficulty ratings of all subprocesses are shown in Appendix A).

Table 2. Behavioral Performance for Each Condition

Conditions	Mean Accuracy ($\pm SD$)	Mean RT ($\pm SD$)	Task Performance ($\pm SD$)
First order	0.94 (± 0.034)	1469.11 (± 181.546)	1646.39 (± 237.284)
Second order	0.81 (± 0.101)	1857.07 (± 36.157)	2550.49 (± 448.080)

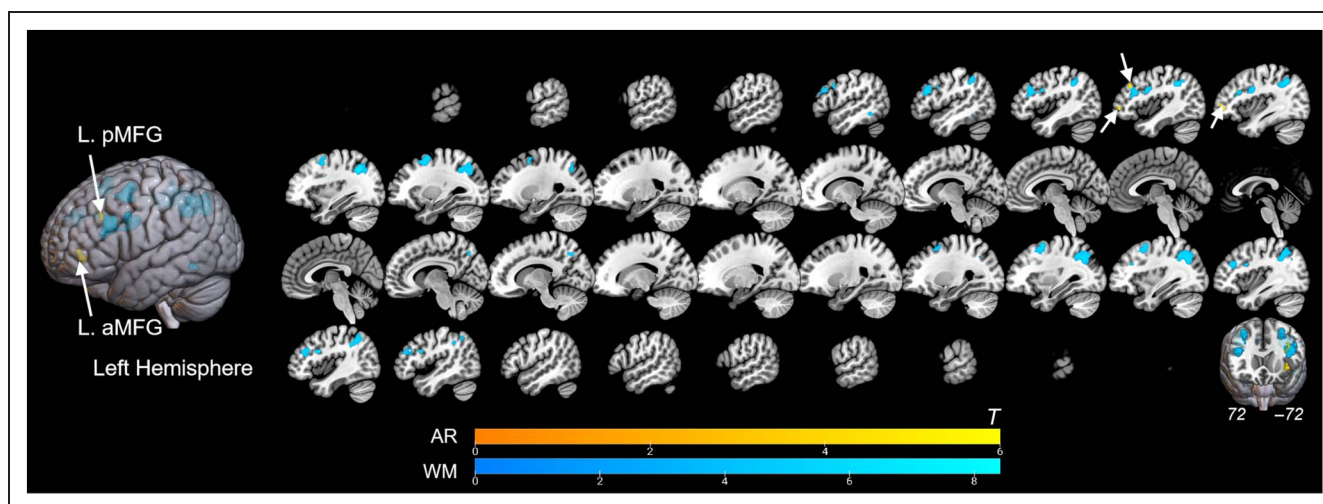


Figure 3. Whole-brain level imaging results. AR = analogical reasoning; WM = working memory.

Each participant completed a semistructured posttask interview, consisting of five questions about possible strategies used to accomplish the tasks. None of the participants reported any misunderstanding of the directions. The participants differed in terms of which strategy they reported employing to solve the tasks. When explaining their task-solving process, participants with higher accuracy adopted more creative tokens such

as numbers or gestures related to the processing of second-order analogies.

Whole-brain Analysis Results

Compared with first-order relational judgment, second-order reasoning elicited greater activation of the left middle frontal gyrus (MFG), including the anterior part

Table 3. Peak Coordinates for the Whole-Brain Comparison

Contrast	Region	K_E	MNI Peak Coordinates (mm)			t Value
			x	y	z	
Whole-brain ($p_{\text{uncorr}} < .0001$, $K_E \geq 10$)						
Analogical reasoning (AR): second-order > first-order	L. pMFG	19	-42	33	39	5.41
	L. aMFG	18	-39	48	-3	5.22
Working memory (WM): complex > simple	L. AG	180	-33	-54	39	8.48
	R. SPL	194	33	-63	36	7.31
	R. MFG	63	33	6	60	6.64
	L. pMFG	64	-30	6	51	6.38
	L. PrG	152	-39	0	30	6.30
	R. aMFG	66	39	33	27	6.22
	R. pMFG	22	39	9	27	6.21
R. PCu	15	12	-69	42	5.11	
Whole-brain, masking out WM ($p_{\text{uncorr}} < .001$, $K_E \geq 30$)						
Analogical reasoning (AR): second-order > first-order	L. pMFG	46	-42	33	39	5.41
	L. aMFG	60	-39	48	-3	5.22

L. = left; R. = right; p = posterior; a = anterior; AG = angular gyrus; SPL = superior parietal lobule; PrG = precentral gyrus; PCu = precuneus.

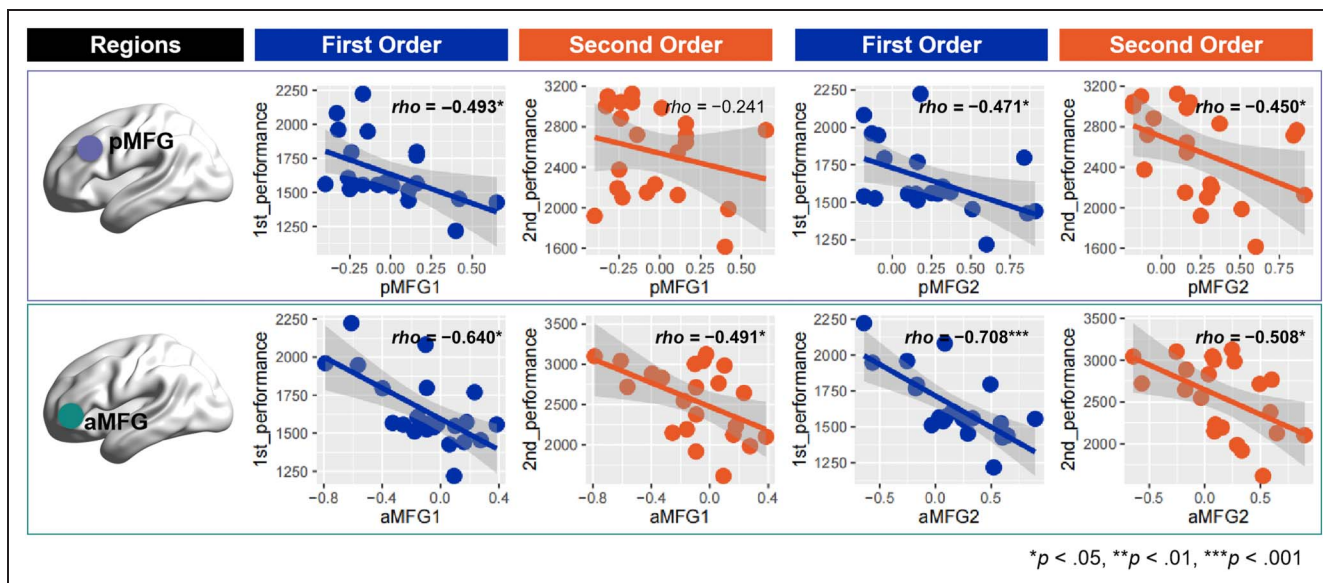


Figure 4. Correlations of the left aMFG and left pMFG with task performances in first-order and second-order analogical reasoning conditions. The blue and orange labels at the top of the table denote in which condition the performance data (i.e., the y axis) were collected. The numbers 1 and 2 after MFG denote in which condition—first- or second-order—the brain activation data (i.e., the x axis) were collected.

(aMFG, part of the rIFC) and the posterior part (pMFG, corresponding to a part of the dorsolateral pFC [dlPFC]). These two areas were partially separable from the working memory regions identified with the contrast of complex working memory > simple working memory, and after masking the working memory regions, the activation of these two regions was still significant ($p_{\text{FWE}} < .05$ at the cluster level; with a more liberal threshold of $p_{\text{uncorr}} < .001$, $K_E \geq 30$ for the consideration of statistical power), as shown in Table 3 and Figure 3. In particular, the left aMFG was activated by analogical reasoning on syntactic patterns in a manner independent of the working memory regions, whereas the left pMFG exhibited partial overlap with the regions associated with the working memory task.

ROI Analysis Results

Because the whole-brain analysis indicated that the left aMFG and left pMFG were the most relevant brain regions for second-order analogical reasoning on syntactic patterns, we selected them as ROIs.

Within-order correlates were fully observed in the left aMFG and left pMFG, as shown in Figure 4. Specifically,

first-order task performance was significantly correlated with the activation of the left aMFG in first-order relational judgments, $\rho(20) = -.64$, $p = .001 < .05$, and with the activation of the left pMFG in first-order relational judgments, $\rho(20) = -.49$, $p = .020 < .05$, whereas second-order analogical reasoning performance was significantly correlated with the activation of the left aMFG in the second-order analogical reasoning task, $\rho(20) = -.51$, $p = .016 < .05$, and the activation of the left pMFG in the second-order analogical reasoning task, $\rho(20) = -.45$, $p = .036 < .05$.

Apart from within-order correlations found in the ROIs, we also discovered cross-order correlations, as presented in Figure 4. Activation levels of the aMFG, $\rho(20) = -.71$, $p < .001$, and pMFG, $\rho(20) = -.47$, $p = .027 < .05$, during the second-order task were significantly negatively correlated with participant performance on the first-order task, whereas only activation of the aMFG (not the pMFG) in the first-order task predicted participant performance on the second-order task, $\rho(20) = -.49$, $p = .020 < .05$.

We analyzed the correlations of left aMFG and pMFG activation with difficulty ratings of all subprocesses of analogical reasoning and found that left pMFG activation in

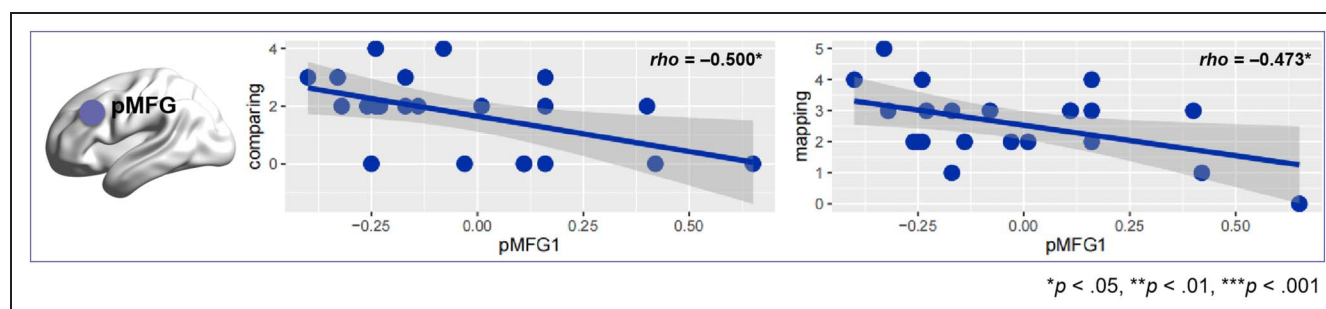


Figure 5. Correlations of the left pMFG with first-order analogical access and analogical mapping.

first-order relational judgments was significantly negatively correlated with the difficulty ratings of first-order analogical access (i.e., recalling the syntactic rule underlying the two terms on the first screen), $\rho(20) = -.50, p = .018 < .05$, and first-order analogical mapping (i.e., matching syntactic patterns on the first and second screens), $\rho(20) = -.47, p = .026 < .05$. Thus, the more active left pMFG was, the less difficult a participant perceived analogical access and analogical mapping to be (see also Figure 5). Such correlations did not preserve in the second-order condition, which could be related to the floor effect of the cap value as 5 when rating the difficulty of the second-order analogical access and analogical mapping, of which 63.64% and 95.45% ratings were 3 and above, respectively.

DISCUSSION

To identify the neural substrates of analogical reasoning on syntactic patterns generated by syntactic rules, the present study adopted the four-term analogy paradigm with two relational orders composed of pseudowords following the Chomsky hierarchy-driven paradigm of artificial grammar processing.

The behavioral results confirmed that all participants were able to complete both the first-order and second-order relational processing, with the latter placing more cognitive demands than the former as measured by RT and accuracy. We further investigated the neural substrates of analogical reasoning evinced in the second-order relational processing by analyzing the fMRI data of participants. Analysis of the fMRI data revealed that the neural correlates of analogical reasoning on syntactic patterns generated by abstract syntactic rules were related to, although slightly different from, those of semantic analogy (Reber et al., 2014; Green et al., 2010, 2012) and visuospatial analogy (Aichelburg et al., 2016; Watson & Chatterjee, 2012), which have been widely researched. Regarding the modulation of brain activity by increased rule complexity, the current findings align well with findings that different reasoning demands are supported by various frontal subregions (Hampshire, Thompson, Duncan, & Owen, 2011). In the current study, syntactic analogies elicited activity in the left aMFG (part of the left rLPFC), similar to the activation elicited by semantic and visuospatial analogies. Moreover, the cross-order predictions of this region for task performance indicated that the left rLPFC is generally involved in analogical reasoning tasks, regardless of higher or lower orders. These results align with the consensus regarding the role of the rLPFC in analogical reasoning in previous research (i.e., that it is fundamental to relational comparison and integration of various forms and orders).

Nevertheless, we regard the role of the left rLPFC in syntactic analogy as universal rather than specific to analogical mapping because we did not find significant correlations between its activation and the difficulty ratings of any subprocesses, which seems to challenge the common assumption that the rLPFC is central to the mapping

subprocess of analogical reasoning but not to other subprocesses (Christoff et al., 2009; Green et al., 2006; Waltz et al., 1999). In their recent review of brain research on analogical reasoning, Parsons and Davies (2022) also pointed out that no conclusive evidence has been found regarding the role of the rLPFC during analogical mapping. Moreover, other studies found similar results as ours that the rLPFC was active throughout the whole process of some high-level cognitive tasks, for example, task planning (Desrochers, Chatham, & Badre, 2015) and complex spatial navigation (Patai & Spiers, 2021). The significant correlation to the whole process but not any specific subprocess could possibly be explained by what Davis et al. (2017) noticed in their relational categorization research that the rLPFC was active when learning a new relation for solving the categorization but would not stay active if relations involved in subsequent problems remained unchanged (e.g., in the present study, the repetition, mirror, and copy patterns were presented in random orders throughout with no new patterns being introduced later). The rivalry between the global versus process-specific hypotheses regarding the functionality of the rLPFC in analogical reasoning has not yet been settled, which underscores the need for further meticulously designed studies delving into this matter.

The MNI peak coordinates for the whole-brain comparison in the current study not only indicated the loci of activation during analogical reasoning on syntactic patterns but also provided data concerning the dorsoventral gradient in the aMFG in terms of relational integration. By comparing second-order visuospatial and semantic trials with first-order trials, Wendelken et al. (2012) found that the MNI activation peak for visuospatial analogies was located dorsal to the peak for semantic analogy. Before the current study, it was unclear whether the activation peak for analogical reasoning on syntactic patterns would be closer to that for visuospatial or semantic analogies because syntactic analogies are similar to both types of analogies—syntax and semantics are closely related because of their interoperability for human language use (Berwick et al., 2013), whereas syntactic rules are abstract, similar to the logical or mathematical rules that can be inferred from visuospatial relationships (Hobeika et al., 2016).

To determine the aMFG locus that supports syntactic analogy in relation to the other two types of analogies, we compared the MNI peak coordinates in our study (see Table 3) with data reported by Wendelken et al. (2012). The averaged peak for analogical reasoning on syntactic patterns across participants found in the present study was located closer to the peaks for semantic analogy of all participants in Wendelken et al.'s (2012) study than to their peaks for visuospatial analogy. The anatomical proximity between semantic peaks and syntactic peaks is in line with the explanation provided by Wendelken et al. (2012), that is, that the domain sensitivity of the aMFG is a result of different anatomical positions of neurons that process different kinds of first-order inputs because the

left ventrolateral pFC (which processes semantics; Binder, Desai, Graves, & Conant, 2009) and the left posterior inferior frontal gyrus (which processes syntax; Matchin & Hickok, 2020) are both ventral to the left superior frontal sulcus (which processes visuospatial information; Sala, Rämä, & Courtney, 2003). However, using only three sets of coordinates of activation peaks across different studies and different groups of participants to generalize the dorsoventral gradient of the aMFG to the domain of syntactic analogy is relatively coarse grained. From the applied perspective, researchers should consider having the same participants work on all three different types of analogical reasoning tasks to test the hypothesis using fine-grained within-participant results. Furthermore, at the group level, the coordinates of the aMFG identified in this study were close to those of semantic analogy; however, the visually presented symbols for reading also contained visuospatial information, especially considering that the word orders of the sequences reflected the spatial arrangements of the symbols. In this sense, we agree with Bahlmann et al. (2009) that as long as the sequential elements are integrated as higher-order structural events, both language and other domains (i.e., the visuospatial domain in their study) might share the neural substrates (i.e., Broca's area in their study). Therefore, we assumed that word orders for deducing/acquiring syntactic rules during reading might be a special case of visuospatial processing in the language domain; this is reminiscent of the hypothesis that human knowledge might be encoded and represented by both language and sensory/motor experiences (Bi, 2021). Nevertheless, although the rLPFC may exhibit a functional gradient, we believe that it is still safe to conclude that this region (especially the aMFG) might support different analogical reasoning tasks with inputs from various cognitive domains (syntactic, semantic, or visuospatial).

In addition to the left aMFG, we also identified the left pMFG, a region located in the dlPFC, as an important brain region for analogical reasoning. This region also partially overlapped with those supporting working memory. Its role in analogical reasoning is supported by previous studies that established strong links between working memory and the dlPFC (Barbey, Koenigs, & Grafman, 2013; Manenti, Cotelli, Calabria, Maioli, & Miniussi, 2010; Petrides, 2000) and that emphasized the high demand for working memory in analogical reasoning tasks (Morrison, Holyoak, & Truong, 2001; Waltz, Lau, Grewal, & Holyoak, 2000). The significant correlations of the left pMFG activation during first-order tasks with the difficulty ratings of two first-order subprocesses—analogue access and analogue mapping—further demonstrated the major roles of the dlPFC in retrieving analogical syntactic rules and linking one rule to the other. These roles of the dlPFC in analogical reasoning on syntactic patterns are also consistent with empirical findings in semantic and visuospatial analogical reasoning (Vendetti & Bunge, 2014; Cho et al., 2010; Krawczyk et al., 2010; Volle et al., 2010).

Finally, different strategies reported by participants in the posttest semistructured interview tap on the renewed exemplar-abstraction debate when accounting for human language: ability (Adger, 2020; Ambridge, 2020a, 2020b; Lieven et al., 2020) and the lexicon–ontology interface in natural language processing (Huang et al., 2010; Hirst, 2009). Our moderate stance was still appropriate in front of these new pieces of arguments and evidence. According to the behavioral data and the interview, participants who reported themselves representing the unfamiliar symbols using numbers or gestures performed slightly better than those who did not, but the difference was not significant. The finding is in line with previous studies on sentence processing using artificial grammar that a deliberate choice of symbols for representation (e.g., numbers, images, and gestures) might facilitate participants' memory of the material but exert very limited influence on successful rule extraction and relational mapping (Chen et al., 2023; Goucha & Friederici, 2015; Pallier, Devauchelle, & Dehaene, 2011). Because conscious abstraction seemed conducive to syntax processing but far from being decisive, we consider that the human language mechanism is less likely to be rooted in any either-or dichotomy (e.g., exemplar or abstraction) but more likely to be based on a multifaceted system supported by various cognitive abilities, just like the strategies used by the participants to memorize the patterns for abstraction could go along with the analogical process. Although addressing the heated debate on language mechanisms and models is beyond the scope of this article, the strategy use revealed in the current experiment sheds light on a possible route to further investigate this issue via strategy-focused measures in combination with neuroimaging data.

Limitations

The present study followed the most basic paradigms—the four-term analogy and the artificial grammar—in research of analogical reasoning and syntax processing, respectively. Although, as we mentioned in the Introduction, this choice was self-restraint to provide a simple and clear reference point for more realistic research on human syntax processing via analogical reasoning in the future, the limitation is inherent in the artificial nature of the symbols and patterns employed and in the particularly well-controlled laboratory environment. Meanwhile, to ensure the direct comparability of this initial study of syntactic analogy to previous studies of visuospatial and semantic analogies, auditory or tactile presentation of syntax was not used, neither were rule violations (i.e., string patterns that followed none of the predetermined artificial patterns) included in the design. Hence, there is still work to be done before we can generalize current findings to the realm of natural syntactic processing and learning *per se*.

Apart from the primary goal of this research to identify the brain regions responsible for analogical reasoning on

syntactic patterns, a secondary goal was to interpret the functionality of each ROI with respect to subprocesses of analogical reasoning. Currently, we did this by correlating participants' difficulty ratings of each subprocess with their ROI activation. However, because of the retrospective nature of posttest ratings, the grain level for the subprocess evaluation was relatively coarse. In addition, the division of the subprocesses, although based on extensive literature (see Parsons & Davies, 2022, for a review), was still subjective. To overcome this limitation, future researchers may develop more elaborate designs by first choosing a mathematical model of cognition that suits the cognitive tasks in hand, then quantifying each subprocess determined by the model, and finally, analyzing the correlations between better-defined subprocess measures and ROIs' activation. This model-based neuroimaging approach (Davis & Goldwater, 2021) takes mathematical models of cognition as measurement tools, which increases the precision and objectivity of the subprocess measurement. Furthermore, although the block design adopted in this research provided high detection power to spot the critical brain ROIs, it was not as sensitive to the signal change between subprocesses as event-related designs. In addition, future designs may make use of functional near-infrared spectroscopy and magnetoencephalography, as supplementary to fMRI, to increase the temporal resolution of neuroimaging data collected.

Conclusion

Our findings offer a nuanced explanation of the brain network that underlies analogical reasoning, with variation according to hemisphere and task complexity. First, the left pMFG activation pattern found in the current study confirms that the left dlPFC is important to analogical

access and analogical mapping, which demand efficient memory retrieval. Second, the left aMFG activation pattern suggests that the task-general function of the rLPFC in relational integration (Hobeika et al., 2016; Waltz et al., 1999) is more likely to permeate the whole process of analogical reasoning than to influence only one or two subprocesses. Third, the closer MNI peak of syntactic analogy found in the present study to that of semantic analogy than to that of visuospatial analogy found in the previous study (Wendelken et al., 2012) again reflects the domain sensitivity of the aMFG as a result of different kinds of first-order inputs; that is, the left ventrolateral pFC, which processes semantics (Binder et al., 2009), and the left posterior inferior frontal gyrus, which processes syntax (Matchin & Hickok, 2020), are both ventral to the left superior frontal sulcus, which processes visuospatial information (Sala et al., 2003).

The present findings enhance our understanding of the task-general function of the MFG in analogical reasoning. The results fit broadly with past findings but specifically suggest that multiple relational operations involving both first-order and second-order analogical reasoning may engage the left pMFG and left aMFG. In addition, we developed a novel analytical tactic for whole-brain analysis in which activation not related to analogical reasoning was removed by masking activated regions during simple and complex working memory tasks that paralleled the first-order and second-order analogical reasoning tasks in terms of procedures and content types. This tactic helped isolate the functional regions dedicated to analogical reasoning.

In conclusion, the present fMRI data support the importance of both the rLPFC and the dlPFC for analogical reasoning, as reported in previous studies, but raise questions about the specific functional role of the rLPFC, especially in the context of analogical reasoning on syntactic patterns, which has not yet been sufficiently studied.

APPENDIX A

Table A1. Difficulty Ratings of Subprocesses in the First-order and Second-order Tasks

<i>Conditions</i>	<i>Subprocesses</i>	<i>Survey Items</i>	<i>Mean Ratings (± SD)</i>
First order	Recognition	Read String (1) on the first screen.	1.36 (± 0.79)
	Recognition	Read String (2) on the first screen.	1.86 (± 0.89)
	Analogical schema induction (Parsons & Davies, 2022)	Infer the rule that produces String (2) from String (1).	2.18 (± 0.85)
	Recognition	Read String (3) on the second screen.	1.23 (± 0.92)
	Catch item	Complete the task by comparing only String (1) and String (3).	0.36 (± 1.05)
	Recognition	Read String (4) on the second screen.	1.68 (± 1.25)
	Catch item	Complete the task by comparing String (1) and String (4).	0.55 (± 1.06)
	Catch item	Complete the task by comparing only String (2) and String (4).	0.41 (± 0.80)
	Analogical schema induction (Parsons & Davies, 2022)	Infer the rule that produces String (4) from String (3).	2.14 (± 0.71)
	Analogical access (Parsons & Davies, 2022)	At the second screen, recall the production rule for the first screen.	1.73 (± 1.35)
	Catch item	Complete the task by comparing only String (2) and String (3).	0.32 (± 1.04)
	Analogical mapping (Parsons & Davies, 2022)	Compare whether the production rules are the same for the first and second screens.	2.59 (± 1.14)
	Analogical inference (Parsons & Davies, 2022)	Apply the production rule for the first screen to String (3) and infer the correct String (4).	0.82 (± 1.40)
	Evaluation	Compare whether String (4) on the second screen is the same as the inferred String (4).	1.27 (± 1.70)
Second order	Analogical access (Parsons & Davies, 2022)	At the fourth screen, recall the relationship between the first and second screens (same/different).	2.73 (± 1.32)
	Catch item	Complete the task by comparing only the first and third screens (same/different).	0.18 (± 0.85)
	Analogical mapping (Parsons & Davies, 2022)	At the fourth screen, compare the relationship (consistent/inconsistent) between the relationship of the third and fourth screens (same/different) and the relationship of the first and second screen (same/different).	3.82 (± 0.85)
	Catch item	Complete the task by comparing only the second and fourth screens (same/different).	0.00 (± 0.00)
	Analogical inference (Parsons & Davies, 2022)	At the third screen, infer the fourth screen based on the relationship between the first and second screens.	0.91 (± 1.60)
	Catch item	Complete the task by comparing only the second and third screens (same/different).	0.09 (± 0.43)
	Evaluation	Compare the fourth screen with the inferred fourth screen (consistent/inconsistent).	1.14 (± 1.81)
	Catch item	Complete the task by comparing only the first and fourth screens (same/different).	0.00 (± 0.00)

Difficulty ratings range from 1 to 5, with 1 indicating the easiest and 5 indicating the hardest. Participants were instructed to rate an item “zero” if the subprocess in the item was not present or not used in their entire process of solving the problem. All catch items received mean difficulty ratings lower than 1, which validates their irrelevance despite their face validity.

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Corresponding author: Luyao Chen, Beijing Normal University, 19 Xinwai Ave., Beitaipingzhuang 100875, China or Department of Neuropsychology, Max Planck Institute for Human Cognitive and Brain Sciences, Stephanstraße 1a, Leipzig, Sachsen 04103 Germany, or via e-mail: luyaochen@bnu.edu.cn.

Data Availability Statement

Data will be made available on reasonable request.

Author Contributions

Zhongshan Li: Formal analysis; Investigation; Methodology; Writing—Original draft. Zhuqian Zhou: Formal analysis; Writing—Original draft. Xiaoling Wang: Project administration; Visualization. Jinshan Wu: Conceptualization; Funding acquisition; Supervision; Writing—Review & editing. Luyao Chen: Conceptualization; Formal analysis; Funding acquisition; Methodology; Resources; Supervision; Writing—Review & editing.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this period were $M(an)/M = .407$, $W(oman)/M = .32$, $M/W = .115$, and $W/W = .159$, the comparable proportions for the articles that these authorship teams cited were $M/M = .549$, $W/M = .257$, $M/W = .109$, and $W/W = .085$ (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance.

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