Relational reasoning as a learned bias: Evidence that generating explanations facilitates relational matching in adults

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Abstract

Reasoning based on relations is essential for human learning and thinking. However, how this ability is acquired remains unclear. Two accounts offer different views: whereas one suggests that relational reasoning is related to cognitive development, the other views it as a learned bias. We conducted two experiments to investigate whether relational reasoning is a learned bias. Experiment 1 tested adults on the Relational Match-to-Sample task. The results revealed that a significant proportion of adults failed to engage in the expected relational reasoning; instead, they relied on the object similarity. Scores on Raven Advanced Progressive Matrices (APM-12) suggest that the preference for similarity is not tied to general cognitive ability. Experiment 2 tested whether similarity-based reasoners can learn relational bias when prompted to generate explanations. The results showed that participants who primarily generated relational explanations successfully learned relational bias. Taken together, this study suggests that relational reasoning is a learned bias.

Keywords: inductive bias; relational reasoning; similarity-based reasoning; RMTS

Introduction

Relational reasoning is a cornerstone of human cognition and refers to the ability to identify and transfer common patterns between events and situations (Holyoak & Lu, 2021; Kroupin & Carey, 2022). For example, water flow in pipes can be used to illustrate electric current in wires, and the orbit of planets can explain electron movement around atomic nuclei. Moreover, many inventions stem from relational reasoning; for instance, the creation of Velcro was inspired by the relationship between cocklebur seeds and animal fur. While relational reasoning is crucial, how humans acquire this ability remains unclear.

Two main accounts provide insights into humans' ability for relational reasoning. One account suggests that relational reasoning is closely related to the cognitive capacity level (Heit & Hayes, 2011; Penn et al., 2008; Richland et al., 2006), whereas the other indicates that it is likely a learned bias (Carstensen et al., 2019; Kroupin & Carey, 2022; Walker et al., 2016). This study aims to investigate whether or not relational reasoning is a learned bias. Two key questions need to be addressed. First, whether a dissociation exists between cognitive capacity and relational reasoning performance. Second, whether relational reasoning can be easily learned from the surrounding information.

Accounting for the acquisition of relational reasoning ability

Two main accounts explain how humans acquire relational reasoning. One is the capacity account, which attributes the relational reasoning ability to high-level cognitive capacity and/or increasing domain knowledge. The other is the bias account, which posits that individuals' reasoning based on similarity or relations is guided by learned biases.

Capacity account This account emphasizes the role of capacity in relational reasoning. Engaging in relational reasoning involves recognizing and representing abstract relations, as well as retaining these relational concepts in memory for later use (Halford, 1993). For example, in a Relational Match-to-Sample (RMTS) task, participants were required to determine which of the relational match (BB) or the object match (AC) matches the target (AA). To perform relational matching, one must first identify and represent the *same* relation in the target, then retain it in working memory to search for matching options. This process involves the engagement of attention (Richland et al., 2006), representation (Penn et al., 2008), and memory (Heit & Hayes, 2011). Moreover, engaging in relational reasoning also requires the involvement of executive function, such as flexibility and inhibition control (Morrison et al., 2004; Thibaut et al., 2010). The capacity account suggests that adults can perform relational reasoning due to the

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development and maturation of these abilities. In contrast, young children and nonhuman animals often fail in relational reasoning due to their underdeveloped or lacking capacities (Christie & Gentner, 2014; Kroupin & Carey, 2022; Simms & Richland, 2019).

Additionally, another aspect of the capacity account focuses on increasing relational knowledge. In some specific relational domains, performing relational reasoning necessitates relevant knowledge or learning experience (Chi et al., 1981; Goswami & Brown, 1990; Rattermann & Gentner, 1998). For instance, individuals lacking knowledge about words' grammar may struggle when reasoning about the grammatical relationships between words (e.g., Does "*run*" go with "*destroy*" or "*and*"?). In this research, we focus on the individuals' reasoning about general and simple "*same-different*" relations. Accordingly, we will concentrate on cognitive ability in the capacity account.

Overall, the capacity account suggests that the maturation of abilities contributes to the acquisition of relational reasoning. However, research in the development field offers a different perspective.

Bias account This account suggests that reasoning is influenced by inductive biases. Developmental research suggests that children possess the ability to reason about relations from an early age. Studies have shown that infants as young as 7 to 9 months can recognize same-different relations (Dewar & Xu, 2010; Ferry et al., 2015). Furthermore, children aged 18 to 30 months can successfully complete a causal relational reasoning task, activating a music box using blocks that are either the same or different (Walker et al., 2016; Walker & Gopnik, 2014). Nevertheless, their relational reasoning abilities showed a puzzling decline as they developed. The failure of older children (aged 4 to 6) to engage in relational reasoning is attributed to a specific inductive bias (Carstensen et al., 2019; Kroupin & Carey, 2022; Walker et al., 2016). This bias refers to preschoolers' tendency to focus on object properties, believing these properties are more likely to relate to other objects or events (Gopnik & Sobel, 2000). Therefore, children are more likely to focus on objects' similarity when reasoning.

It is probable that inductive reasoning is guided by such biases, which help narrow down possibilities to a manageable few within any given context. Without these biases, identifying relevant information would be challenging (Goodman, 1955; Kroupin & Carey, 2022). From this perspective, relational reasoning is likely another inductive bias that individuals acquire.

To address whether relational reasoning is a learned bias, it is necessary to determine if it is independent of cognitive ability level. Furthermore, biases, as beliefs, should be adaptable and could be influenced by surrounding information in a short period. Therefore, it is also essential to investigate whether relational reasoning can be learned rapidly. Indeed, an increasing body of research has emerged to support the bias account from these two perspectives.

Support for the bias account

Next, we reviewed the evidence supporting the notion that relational reasoning may be a learned bias from two perspectives: 1) whether or not some adults with mature cognitive abilities struggle to use relations when reasoning, and 2) whether or not individuals can learn relational reasoning bias rapidly.

Adults may struggle to perform relational reasoning There is limited evidence regarding whether adults fail to engage in relational reasoning, as they are generally considered effective reasoners who are more likely to rely on reliable relations or structures (e.g., category) (Bright & Feeney, 2014; Deng & Sloutsky, 2015; Murphy & Ross, 2005, 2010). A recent study examined adults' reasoning performance on an ambiguous RMTS task and revealed that a significant proportion of adults rely on object similarity rather than relations to make reasoning (Kroupin & Carey, 2022). In the RMTS task, adult participants were presented with a triad consisting of a target (e.g., two quarter-circles, relation: same), a relational matching pair (e.g., two trapezoids, relation: same), and an object matching pair (e.g., a quarter-circle and an irregular triangle, relation: different). The relational matching pair shares the same relation with the target, and the object matching pair shares the same object (the quarter-circle). Adults had to decide which matching pairs matched the target. Results indicated that nearly half of the participants (41%) opted for similarity-based reasoning by matching the object matching pair to the target.

This finding suggests that even adults are struggling to perform relational reasoning in certain situations. It indicates a gap between the cognitive capacity level and relational reasoning ability. However, researchers also noted that these results may stem from individual differences in cognitive capacities. We will explore this further in this study.

Relational reasoning can be facilitated Developmental research provides ample evidence that relational reasoning can be learned quickly. For example, Walker et al. (2016) demonstrated that providing 3-year-olds with evidence against their specific bias enhanced their performance in the casual relational reasoning task. After observing each single block could not activate the music box, children were more likely to select the correct relational matching blocks. Furthermore, many approaches have been found to facilitate children's relational reasoning in tasks that do not involve casual relations, which are typically more challenging for children, such as using labels (Christie & Gentner, 2014), making comparisons (Gentner et al., 2011; Thibaut & Witt, 2023), stimulating children's relational thinking (Kroupin & Carey, 2021; Simms & Richland, 2019; Walker et al., 2018), and asking them to explain (Brockbank et al., 2022).

Asking children to explain is a newly discovered approach to changing their inductive bias from object priority to relation. Research suggests that the process of generating explanations prompts children to consider a broader range of hypotheses, thereby increasing the likelihood that they transfer to relational reasoning (Walker et al., 2016). Research further revealed that 5- and 6-year-olds (Brockbank et al., 2022) and 4- and 5-year-olds (Yang et al., 2024) can succeed in the RMTS task immediately after interacting with an adult who demonstrates relational matches and generates explanations for their own and the adult's choices. Overall, these findings indicate that relational reasoning is a bias that can be learned in a short time.

The present study

This study aims to investigate how humans acquire relational reasoning ability. Two main accounts provide insights into this question. One account suggests that relational reasoning ability results from the maturation of cognitive capacities, while the other indicates that it is a learned bias. To explore whether relational reasoning is a learned bias, this study tested reasoning performance in adults by using an ambiguous RMTS task.

Two experiments were involved in this study. In experiment 1, we tested whether a dissociation exists between cognitive capacity and relational reasoning performance in adults. The task and procedure were similar to Kroupin and Carey (2022) (Experiment 2). Furthermore, we employed a brief 12-item version of the Raven Advanced Progressive Matrices (APM-12) (Arthur & Day, 1994) to assess individual differences in general cognitive abilities. According to previous research, we predicted that nearly half of the adult participants would perform matching based on object similarities rather than relations. If relational reasoning is a product of development of capacity, we would expect to observe differences in general cognitive abilities among adults with different reasoning strategies.

In Experiment 2, we investigated whether relational reasoning can be learned by individuals who initially engage in similarity-based reasoning. Participants who demonstrated similarity-based reasoning in Experiment 1 took turns completing the RMTS task with an experimenter who demonstrated relational reasoning. They were required to explain the reasoning behind the choices made by either the experimenter or themselves (training phase). Next, participants completed a final matching test by themselves (test phase). No corrective feedback was provided throughout the entire experimental process. We predicted that participants would demonstrate more relational matches after generating explanations, indicating that they learned the relational bias from the current context.

Experiment 1

Method

Participants We recruited 62 (M_{age} = 19.45, *SD* = 1.35, 48 females) right-handed, fluent Mandarin undergraduate students from a university through the SONA system, with all participants receiving bonus points in their courses.

Materials and Procedure We adopted the version of the RMTS task proposed by (Kroupin & Carey, 2022). This task included 8 distinct triads, with each triad consisting of three cards featuring geometric figures: the target (e.g., two quarter-circles), the relational match (e.g., two trapezoids), and the object match (e.g., a quarter-circle and an irregular triangle). The relational matching cards and the target always share the same relation (*same*), while the object matching cards and the target share the same object (e.g., the quarter-circle). Each figure appeared in only one triad and differed in shape and color, while maintaining approximately equal height and width. The left and right positions of the relational and object-matching cards are balanced, and each triad appears in a random order. Only the *same* relation was involved in Experiment 1.

The participants were seated in a quiet, well-lit room, where they observed the computer presenting the triads. The three cards in each triad were presented simultaneously. In each triad, participants were asked to decide which card matched the target by pressing the corresponding button. The formal experiment began after the participants complete two practice trials. After the formal experiments, participants completed the untimed APM-12 test (Poulton et al., 2022) using a paper-based format, and their scores were recorded (9 missing values). After the experimenter read the standardized instructions of APM, participants completed the test and recorded their answers on a separate answer sheet. The test concluded when all 12 questions were answered. This study was not preregistered.

Coding Selecting the relational match was scored as "1," while choosing the object match was scored as "0." Thus, the total matching score for each participant was "8."

A strict criterion was applied to distinguish between individuals who prefer relational reasoning and those who prefer similarity-based reasoning (Kroupin & Carey, 2022). Participants scoring 1 or less were classified as similarity-based reasoners, and those scoring 7 or more as relational reasoners.

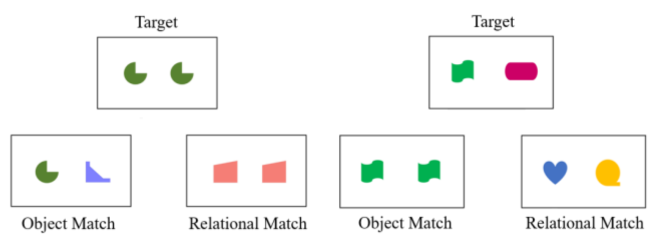

Figure 1: Sample triads of Experiment 1 and 2. A triad included a target, a relational match, and an object match. The left triad presents *same* condition, and the right presents *different* condition. Experiment 1 only contained *same* condition, Experiment 2 contained both *same* and *different* conditions.

Results and Discussion

As we predicted, a large proportion of participants engaged in similarity-based reasoning rather than relational reasoning. Even under strict criteria (matching score ≤ 1), 39% of participants consistently preferred object matching. In addition, only 48% preferred relational matching. The distribution significantly differs from the null hypothesis, which assumes that all adults engage in relational reasoning,

$\chi2(1) = 56.64$, $p < .001$. Notably, the distribution does not significantly differ from an even split, $\chi2(1) = .50$, $p = .48$. We further examined the distribution of adults' biases at the trial level and found that adults are roughly evenly split as to which basis of matching they chose: 46% of all responses were object matches, and 54% were relational matches, $\chi2(1) = .32$, $p = .571$.

We compared the APM-12 scores of similarity-based reasoners and relational reasoners and found no strong evidence that individual biases were influenced by general cognitive ability. The scores for similarity-based reasoners ($M = 8.65$, $SD = 1.81$) and relational reasoners ($M = 9.32$, $SD = 1.97$) were similar, t (43) = 1.17, $p = .247$, 95% CI = [-.48 1.82]. For the 8 participants who did not belong to either similarity-based or relational reasoners, the mean score was 9.25 ($SD = 1.39$). No ceiling or floor effects were observed, APM-12 scores for 53 participants (9 missing values, including 5 relational reasoners and 4 similarity-based reasoners) ranged from 5 to 12 ($M = 9.06$, $SD = 1.83$).

Overall, Experiment 1 demonstrated that many adults engage in similarity-based rather than relational reasoning, suggesting that relational reasoning is not merely a result of cognitive maturity. Next, we explored whether adults who initially performed similarity-based reasoning can learn relational bias by generating explanations.

Experiment 2

Method

Participants Twenty-three undergraduate students ($M_{age} = 19.52$, $SD = 1.53$, 16 females) with a matching score of 1 or less in Experiment 1 participated in this experiment. One additional participant was excluded due to a procedural error that resulted in missing explanations

Materials and Procedure The experiment comprised two phases: a training phase and a test phase. Participants were required to complete the RMTS task in both phases, with materials and procedures similar to those in Experiment 1. Additional materials were created based on (Kroupin & Carey, 2022). To gain a broader perspective on relational reasoning, we also introduced *different* relation-matching conditions, where the target presents two figures that differ in shape and color, along with the relational matching card (see Figure 1).

During the training phase, participants and the experimenter took turns completing the matching task, beginning with the experimenter. In the experimenter's trials (Trial 1 and Trial 2), participants pressed a button to reveal the experimenter's choice after the triad was presented. A red circle then appeared on the relational matching card to indicate the experimenter's choice. Participants pressed a key to end the trial after viewing the experimenter's selection. In all experimenter's trials, the experimenter's choice was the relation matching card. In the participants' trials (Trial 3 and Trial 4), participants made choices and pressed a button. The training phase included 12 trials (6 trials for *same* condition, 6 for *different* condition), with the experimenter and participants each completing two trials at a time. After each trial, participants were asked to explain why the experimenter or themselves made such a choice by entering their explanations in a pop-up window. The participants' matching choices (6 in total) and their explanations (12 in total) were recorded. Then, participants were required to complete the test phase.

During the test phase, participants completed 8 trials of the matching task, consisting of 4 trials in the *same* condition and 4 trials in the *different* condition. Their choices were recorded.

Coding As in Experiment 1, selecting the relational match was scored as "1," while choosing the object match was scored as "0." The total matching scores for the training and test phases were 6 and 8, respectively.

Participants' explanations were coded as belonging to one of four broad categories: 1) object focused ("Because both cards have the square," "The card on the left has the same graphic as the card above."), 2) relation focused ("Because graphics on the left are same, similar to the top," "Graphics on both cards are different."), 3) other ("because the experimenter made the wrong choice," "The grey shape looks like smoke."), and 4) no responses ("I don't know.") (similar to Brockbank et al., 2022). Explanations were coded as relation focused if they included any mention of relational properties, even when object properties were also mentioned. Two individuals coded the explanations separately, and their results were compared for agreement. Inter-rater reliability was high at 92%, with any minor discrepancies resolved by a third party.

Results and Discussion

As shown in Figure 2, observing demonstrations and generating explanations facilitated a shift in adults' inductive bias. In contrast to Experiment 1, where participants engaged in absolute similarity-based reasoning ($M = .02$), participants in Experiment 2 exhibited an ambiguous preference, as the proportion of relational matches increased to chance levels (0.5) under the *same* conditions, $t_{training}$ (22) = -.69, $p = .498$, 95% CI = [-.26 .13]; t_{test} (22) = .65, $p = .52$, 95% CI = [-.14 .27].

Notably, generating explanations is particularly crucial for facilitating relational reasoning (see Figure 3). Although all participants observed the experimenter's demonstration of relational reasoning, only those (11 out of 23) who predominantly generated relational-focused explanations across the 12 trials exhibited significantly higher proportions of relational matches than the chance level under the *same* conditions in the test phase ($M = .84$), t (10) = 3.15, $p = .01$, 95% CI = [.10 .58], Cohen's $d = .95$. They also showed a higher proportion of relational matches than chance in the training phase ($M = .76$), with the difference approaching significance, t (10) = 2.15, $p = .057$, 95% CI = [-.01 .52], Cohen's $d = .65$. Taken together, our results indicate that adults can learn relational bias by generating explanations.

In addition, our findings revealed several intriguing aspects regarding the facilitative effect of generating explanations. First, some adults who did not use relations in their explanations (11 for object focused, 1 for other) still engaged in similarity-based reasoning under both *same* and *different* conditions during the training and test phases (see Figure 3). Second, the effect of generating explanations on relational reasoning is influenced by the type of relation; the proportion of relational matches under the *same* condition is higher than under the *different* condition (see Figure 2). Third, the facilitative effect of explanations appears to be delayed, as the proportion of relational matches in the test phase is significantly higher than in the training phase under the *same* conditions (see Figure 2).

Overall, Experiment 2 indicates that adults' inductive bias can be shifted through the process of generating explanations. Participants who focused on and utilized relational aspects while generating explanations successfully acquired a relational bias.

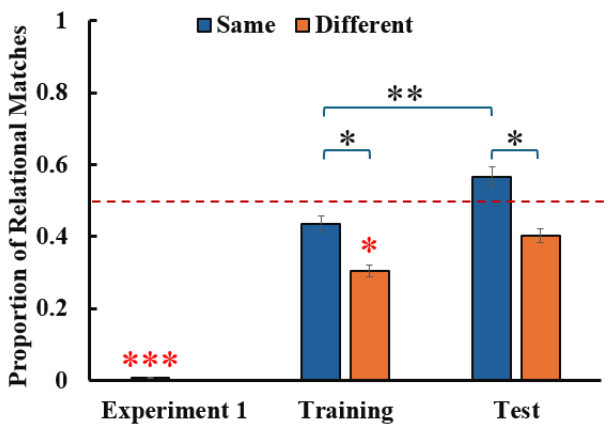

Figure 2: Proportion of relational matches of *same* condition in Experiment 1, and those of *same* and *different* conditions under training and test phases in Experiment 2. The chance level is 0.5. Error bar present standard errors of mean.

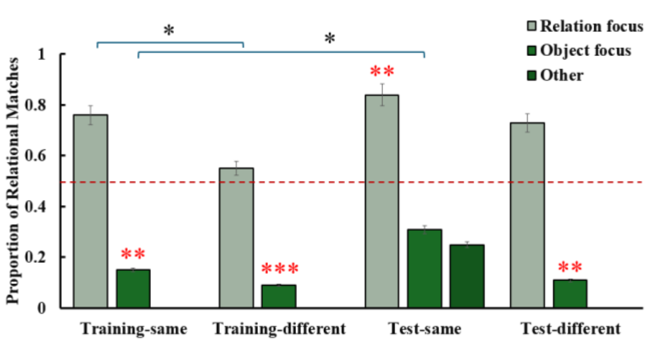

Figure 3: Proportion of relational matches for *same* and *different* conditions in training and test phases among participants of the three explanation types. The chance level is 0.5. Error bar present standard errors of mean.

General Discussion

Across two experiments, we assessed adults' relational reasoning performance (Experiment 1) and investigated whether adults can learn relational reasoning by generating explanations (Experiment 2). In experiment 1, we replicated Kroupin and Carey (2022) finding that a significant proportion of adults engage in similarity-based reasoning instead of relational reasoning. We also included a Raven APM-12, which revealed that differences in reasoning preferences were not linked to variations in general cognitive abilities. These findings suggest that relational reasoning is not fully attributed to the ability maturity. We further tested this idea by examining whether adults can learn relational bias in reasoning. Results showed that after observing relational clues in the context and generating explanations, participants who focused on and utilize relations to generate explanations learned relational reasoning. Overall, our findings suggested that relational reasoning is a learned bias.

The acquisition of relational reasoning in humans has long been a significant area of research. Previous studies indicate a continuous developmental trajectory from similarity-based reasoning to relational reasoning. However, developmental research suggests an early emergence of this ability followed by a decline, indicating that the development of relational reasoning may follow an inverted U-shaped curve. These hypotheses primarily stem from an expectation that adults should engage in relational reasoning (Walker et al., 2016). Our study, however, reveals that many adults do not spontaneously utilize relational reasoning. This finding suggests that the development of relational reasoning ability and its application may be distinct processes. Individuals may possess the potential for relational reasoning from an early age, while their later preferences for either similarity-based or relational reasoning could reflect learned biases.

The formation of inductive biases may be closely linked to language development. Research suggests that children's early word learning is primarily focused on objects (e.g., Gentner, 1982; Waxman & Markow, 1995), which may lead to a preference for object similarity in their reasoning processes. In adults, relational nouns constitute nearly half of the nouns in a representative vocabulary corpus (Asmuth & Gentner, 2005). Consequently, some adults may spontaneously develop a relational bias in their reasoning. For those individuals who retain a specific inductive bias, encouraging their access to and use of relational language or concepts—by prompting them to explain—facilitated a shift from absolute similarity-based reasoning (mean matching score: .02) to relational reasoning (mean matching score for individuals who provided relational explanations: .75 for training phase and .85 for test phase in the same condition). Additionally, cross-cultural evidence suggests that inductive biases are influenced by language. For instance, research has demonstrated that Chinese children perform better in abstract reasoning than Western children (Carstensen et al., 2019; Long et al., 2012). This difference can be attributed to the distinct language environments: Chinese children are exposed to a verb-centered environment that encourages a focus on relationships, whereas the English language environment is noun-centered, leading children to focus more on individual entities (Carstensen et al., 2019).

Our study also offers new insights into how explanation generation promotes relational reasoning. Explanation generation is a recently identified method in developmental psychology that effectively shifts children's inductive bias from similarity to relational thinking (Brockbank et al., 2022; Walker et al., 2016). The researchers suggest that the process of generating explanations encourages individuals to consider a broader range of possibilities, thereby breaking existing biases. Our results further revealed that language plays a crucial role in the effects of generating explanations on relational reasoning. Findings from Experiment 2 showed that only adults who used relational language or concepts engaged in relational reasoning, while those providing object-based or other types of explanations did not demonstrate relational reasoning. This suggested that a willingness to rely on linguistic or conceptual structures may be essential for achieving abstract reasoning, as adults can easily identify and access same-different relations.

Our study also found that the effect of generating explanations on relational reasoning varies by relation type. In both the training and test phases, participants in the same conditions had significantly higher matching scores than those in the different conditions. This may be due to the greater challenge of matching different relations, which requires subjects to assess relations among four figures with distinct shapes and colors. In contrast, matching the same relations involves simply identifying two pairs of figures that are identical in both shape and color. Additionally, our results suggest that it takes time for generating explanations to overcome adults' reasoning biases, as participants' matching scores in the same condition improved from the training phase to the test phase. This indicates that adults tend to adopt a conservative strategy, clinging to their prior expectations. Even when presented with evidence contrary to their beliefs, they need adequate time to accept and internalize a new strategy. This is further illustrated by the low consistency in adults' explanations for the experimenter's choice (74% provided relational explanations) compared to their own (48% provided relational explanations).

Whie the current study indicates that relational reasoning may be a learned bias shaped by language environments, there are several open questions to be addressed in future research. First, it is unclear why some adults develop relational biases while others exhibit specific biases similar to young children. One possibility is that these differences stem from varying language contexts. Numerous studies have reported differences in relational reasoning performance among speakers of different languages, such as Chinese, English, and Korean. For instance, Korean adults have shown greater sensitivity to tight-loose relations compared to English-speaking adults and infants raised in English environments (Hespos & Piccin, 2009; Hespos & Spelke, 2004). Our study was conducted in a linguistically diverse area, with participants speaking various native languages, including Vietnamese, English, Cantonese, and Mandarin. Consequently, our participants exhibited distinct biases.

Second, further research is needed to determine whether it is language itself, or the concepts represented by language that influence the reasoning process. In the current study, separating relational language from concepts is challenging, as they are closely intertwined. We suggest that language, rather than concepts, affects relational reasoning based on the following evidence. Christie and Gentner (2014) found that nonsensical language labels, such as *Truffect*, have a facilitative effect similar to relational labels like *same* or *different*. Additionally, using different language labels to name a feature has been shown to impact children's relational reasoning performance (Hurst & Cordes, 2019). Finally, further research is needed to identify when relational reasoning ability matures. Studies indicate that children recognize and use relations early, but they encounter tasks of varying difficulty (Brockbank et al., 2022; Carstensen et al., 2019; Christie & Gentner, 2007, 2014; Gentner et al., 2011; Walker et al., 2016). Therefore, more research is needed to reach clear conclusions.

Although our study indicates that relational reasoning ability is not attributed solely to cognitive development, cognitive capacity does matter for abstract reasoning. Cognitive aging (Todd et al., 2019) and damage to the prefrontal brain regions influence abstract reasoning performance (Krawczyk et al., 2008; Waltz et al., 1999). Mature cognitive abilities provide the foundation for acquiring relational reasoning.

In summary, our study suggests that relational reasoning is a learned bias. This bias may be linked to language development, as individuals who engage with language in their reasoning are more likely to perform abstract relational reasoning.

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