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Olivier Mascaró, Nicolas Goupil, Hugo Pantecouteau, Adeline Depierreux, Jean-Baptiste Van der Henst, et al.. Human and animal dominance hierarchies show a pyramidal structure guiding adult and infant social inferences. *Nature Human Behaviour*, 2023, 7 (8), pp.1294-1306. <10.1038/s41562-023-01634-5>. <hal-04193958>

**HAL Id: hal-04193958**

**<https://hal.science/hal-04193958v1>**

Submitted on 3 Oct 2023

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**Human and animal dominance hierarchies show a pyramidal structure  
guiding adults and infants social inferences**

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**Abstract**

This research investigates the structure of social hierarchies. We hypothesized that if social dominance relations serve to regulate conflicts over resources, then hierarchies should converge towards pyramidal shapes. Structural analyses and simulations confirmed this hypothesis, revealing a triadic pyramidal motif across human and nonhuman hierarchies (114 species). Phylogenetic analyses showed that this pyramidal motif is widespread, with little influence of group size or phylogeny. Furthermore, nine experiments conducted in France found that human adults ( $N = 120$ ) and infants ( $N = 120$ ) draw inferences about dominance relations that are consistent with hierarchies' pyramidal motif. In contrast, human participants do not draw equivalent inferences based on a tree-shaped pattern with a similar complexity as pyramids. In short, social hierarchies exhibit a pyramidal motif across a wide range of species and environments. From infancy, humans exploit this regularity to draw systematic inferences about unobserved dominance relations, using processes akin to formal reasoning.

### **Main text**






The distribution of social power and wealth in societies are often represented as pyramids<sup>1,2</sup>. In many institutions (e.g., firms or states), the distribution of formal ranks, statuses, and rewards are pyramidal, with fewer individuals at the top than at the bottom<sup>3,4</sup>, sometimes in cases where non-pyramidal organizations might yield better team performance<sup>5</sup>. While this pyramidal distribution could result entirely from historical contingencies in human societies, we argue that this hierarchical shape has a much deeper basis that goes back to the structure of social dominance networks.

We define dominance as a social relation where dominant individuals tend to prevail when their goals conflict with those of their subordinates<sup>6,7</sup>. Social dominance relations are observed in a wide range of human and animal societies<sup>8,9</sup>. Dominant individuals predominantly control access to resources, typically through coercion but also through a variety of other strategies<sup>10-14</sup>. We also assume that social structures involve three individuals or more<sup>15</sup>.

The evolution of dominance hierarchies is linked to conflict avoidance and resolution. Full-blown conflicts are extremely costly in many species, routinely leading to major injuries and even death. Thus, there is strong selective pressure for mechanisms lowering the costs of conflict<sup>16,17</sup>. Stable dominance relations, with subordinates yielding to dominant ones, are hypothesized to function as a means of regulating resource access while avoiding costly conflicts<sup>10-12,18,19</sup>.

Under the hypothesis that dominance regulates conflicts over resources, triadic pyramids (one individual dominating two others who have no dominance relation between them) should be more frequent than triadic trees (two individuals who have no dominance relation between them dominating a third individual), despite the two structures having similar complexity (Fig. 1a). In a triadic tree, multiple individuals occupy the top position and

have the same priority regarding access to resources, creating an opportunity for conflict between the two dominant individuals whenever resources can be monopolized. In contrast, a triadic pyramid involves one dominant individual that can monopolize resources, leaving fewer opportunities for conflicts between subordinates. In short, triadic pyramids are better than triadic trees at regulating conflicts. Thus, if dominance mechanisms down-regulate the costs of conflicts, they should favor the emergence of triadic pyramids at the expense of triadic trees. The conflict-regulatory hypothesis of dominance also explains other structural regularities of social hierarchies, such as dominance transitivity (Fig. 1b).

Pattern	<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;"> <b>a</b>                  Triadic pyramid   </div> <div style="text-align: center;">                 Triadic tree   </div> </div>	<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;"> <b>b</b>                  Transitive   </div> <div style="text-align: center;">                 Chain   </div> <div style="text-align: center;">                 Circular   </div> </div>
Regulation of conflicts	Regulated if the resources can be monopolised by A  Otherwise conflicts between B & C	Not regulated  Conflicts between A & B
Structural regularity (predicted by the conflict-regulatory hypothesis)	Pyramidal structure	
	Transitivity of relations	

*Figure 1. Structural predictions based on the conflict-regulatory hypothesis. a. Overrepresentation of pyramids relative to trees. We posit that the cost of conflicts is better down-regulated by triadic pyramids than by triadic trees. Thus, if dominance mechanisms serve to lower the cost of conflicts, they should favor the emergence of dominance hierarchies showing a pyramidal motif, with an overrepresentation of triadic pyramids relative to trees. b. Overrepresentation of transitive structures relative to circular and chain triadic patterns. In a transitive structure ( $A > B$ ,  $B > C$ ,  $A > C$ ), each individual has a distinct level of priority of resource access. Thus, as long as the dominance relations remain stable, conflict over resources is down-regulated in this structure ( $B$  and  $C$  yield to  $A$ , and  $C$  yields to  $A$  and  $B$ ). By contrast, in a chain ( $A > B$ , and  $B > C$ ), the individuals at both ends of the chain ( $A$  and  $C$ ) have the same level of priority of resource access, thus creating an opportunity for conflicts over resources. Similarly, in a circular structure ( $A > B$ ,  $B > C$ ,  $C > A$ ), there is no way to determine which individual has priority for accessing resources based on dominance relationships (assuming that all individuals from the structure are co-present). This situation creates an opportunity for conflicts between all the individuals in the circular triad. In short, triadic transitive structures are better than circular structures and chains at reducing the number of conflicts. Thus, if dominance mechanisms down-regulate the costs of conflicts, triadic transitive structures should be overrepresented in dominance networks, unlike circular and chain patterns.*

Dominance relations are characterized by their strong tendency to be transitive, and plenty of dominance structures are completely linear<sup>8,20,21</sup>. Notwithstanding, other structural regularities have been observed in dominance hierarchies. In line with the conflict-regulatory hypothesis, animal hierarchies are sometimes pyramidal in shape, with one individual dominating over a group of subordinates<sup>22-26</sup>. Moreover, in many animal hierarchies, triadic pyramids are more frequent than in matched randomized networks<sup>27,28</sup>. A long-standing debate is whether human and non-human hierarchies are similar, and if so, under what conditions<sup>14,29-32</sup>. Here, we addressed this question via a comparison of human hierarchical structures with dominance data from multiple animal species and environments.

We also investigated the human capacity to infer unobserved dominance relations based on the assumption that they are likely to be pyramidal in shape. Given the importance of dominance relations to group organization, being able to map them in one's own environment is crucial<sup>9,33-36</sup>. When an individual cannot directly observe interactions, knowledge of a hierarchy's shape is key to guiding inferences about social relations<sup>34,35,37-42</sup>. For instance, dominance relations tend to be transitive: if A dominates B and B dominates C, then it is likely that A dominates C<sup>20,34,43</sup>. Human adults, infants, and several animal species exploit this structural regularity to draw transitive inferences about unobserved dominance relationships<sup>44-49</sup>. This capacity is remarkable because it involves spontaneous inferences akin to formal reasoning and does not appear to require teaching. While transitive reasoning has been under intense research scrutiny, little is known about the capacity to draw inferences based on expectations about the pyramidal shape of a social structure. Here, we tested the ability of human adults to infer relationships based on expectations about a pyramidal dominance structure and probed the ontogeny of this ability in human infants.

To summarize, this research aimed to investigate the pyramidal shape of dominance structures, and its consequences for humans' social inferences. Studies 1<sub>ab</sub> analyzed and compared the structure of dominance networks in children and in a large set of non-human species. These analyses revealed a consistent triadic pyramidal motif across human and non-human hierarchies. Next, we investigated whether humans expect hierarchies to be pyramidal, and infer novel dominance relationships accordingly. Three experiments (Studies 2–4) revealed that human adults draw inferences consistent with a pyramidal dominance hierarchy. Six additional experiments demonstrated that such inferences are made by infants before any explicit teaching about hierarchies can occur (Studies 5<sub>ab</sub>–7<sub>ab</sub>).

## **Results**

### **The triadic pyramidal shape of hierarchies**

We compared the relative frequency of triadic pyramids and triadic trees (two structures of equivalent complexity). If dominance structures are predominantly pyramidal, then triadic pyramids should be more frequent than triadic trees. Study 1<sub>a</sub> analyzed the structure of children's social hierarchies and compared them to patterns observed in non-human animals (hereafter, "animals"). For human data, we searched the literature for observations of conflict outcomes in children's groups (20 groups; > 5900 interactions, mean group size = 13.85, average-age range = 13–74 months). We used children data because they result from ethological observation, just like animal data. For animal data, we used a large archive of agonistic interactions from multiple species<sup>50</sup>. Data from 113 animal species fulfilled our study's inclusion criteria (298 groups; > 166241 interactions, mean group size = 14.71; see Methods). In Study 1<sub>a</sub>, we grouped animal data by taxonomic category: primates, carnivores (Carnivora), rodents (Rodentia), ungulates (Artiodactyla), birds (Passeriformes), social insects (Hymenoptera), and other species (see Methods). We used data on the outcome

of conflicts to generate dominance networks for each group. For each dyad, the individual who won conflicts more frequently was considered dominant, while the other was considered subordinate.

For each network, we computed the triadic pyramidal metric (1), a normalized index of the amount of triadic pyramids relative to triadic trees.

$$(1) \text{ triadic pyramidal metric} = \frac{N \text{ pyramids}}{N \text{ pyramids} + N \text{ trees}}$$

The average triadic pyramidal metric was significantly higher than predicted by chance in each taxonomic category (Fig. 2a, all  $p$ s < .05; see detailed statistics in Tables S1-3), indicating that triadic pyramids are overrepresented in dominance networks.

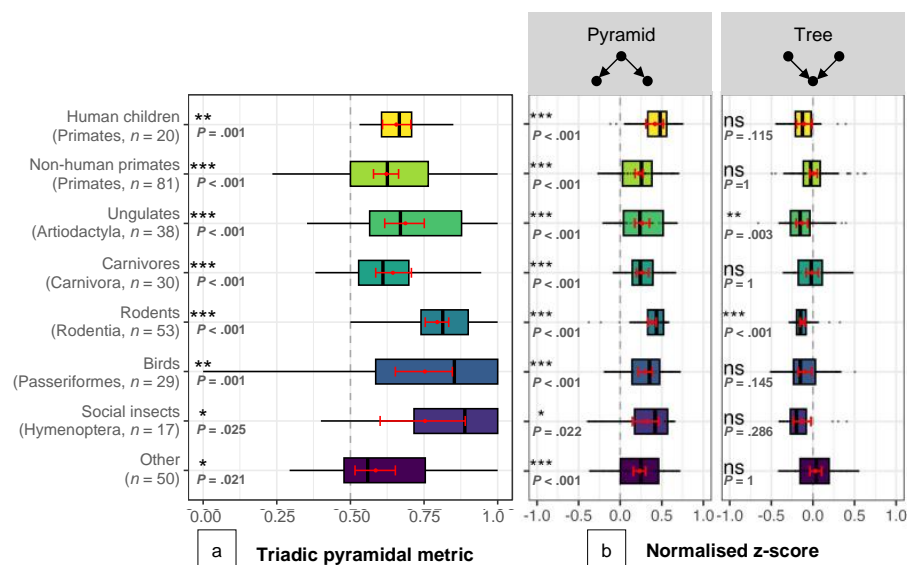


Figure 2. Assessment of pyramidal shape per taxonomic category ( $N = 318$  independent groups). a. Triadic pyramidal metric. b. Normalized z-scores for triadic pyramids and triadic trees. The dotted gray line represents chance (0.5). Red dots and error bars indicate means and bootstrapped 95% confidence intervals (CIs); vertical bars within boxes indicate medians, and boxes indicate the middle two quartiles; right whiskers represent data up to 1.5 times the interquartile range above the third quartile, and left whiskers represent data up to 1.5 times the interquartile range below the first quartile; each grey dot represents data from one social group. P values were assessed with two-tailed one-sample Wilcoxon tests, and were corrected for multiple comparisons across taxonomic groups using the Holm-Bonferroni procedure. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ , ns: not significant.

Subsequently, we investigated whether the high triadic pyramidal metric originated from excess triadic pyramids, scarce triadic trees, or both. Observed frequencies of triadic patterns were compared to chance using simulations<sup>28,51–53</sup>. For each real network, we generated 1000 simulated networks, keeping the positions of edges (relationships) and nodes (individuals) constant while randomizing the direction of dominance relations. The number of times each triadic pattern occurred per simulated network was counted. Next, we computed Z-scores (2) measuring the relative abundance of each triadic pattern in a real network compared with their frequency in simulated networks.

$$(2) Z_i = \frac{Nreal_i - Msim_i}{SDsim_i}$$

where  $Nreal_i$  is the frequency of pattern  $i$  in the observed real network, while  $Msim_i$  and  $SDsim_i$  are the mean and standard deviation of  $i$  frequency across simulated networks, respectively.

These Z-scores were normalized to obtain significance profiles (3) for comparison across groups of different sizes<sup>51,54</sup>. A positive normalized Z-score indicates that a pattern is more abundant in the real network than in the corresponding simulated networks, whereas a negative normalized Z-score indicates the opposite.

$$(3) \text{Normalized } Z_i = \frac{Z_i}{\sqrt{\sum(z_i^2)}}$$

Simulation results confirmed the presence of a pyramidal motif. In line with previous research, this pattern was observed across a wide range of animal species<sup>22–28</sup>. Moreover, we found a comparable pyramidal motif in human children. Average normalized Z-scores were significantly higher for triadic pyramids than for triadic trees in children and in animals (all  $p$ s

< .05, Table S2). Moreover, average normalized Z-scores for triadic pyramids were significantly higher than chance for all taxonomic groups (all  $ps < .05$ , Fig. 2b, Table S3). Thus, triadic pyramids are more abundant in real dominance networks than in comparable randomized networks. In contrast, average normalized Z-scores for triadic trees did not differ significantly from chance in any group except rodents and ungulates, where the Z-scores were significantly below chance. Thus, the high triadic pyramidal metric observed in children and animals results primarily from an overabundance of triadic pyramids. In rodents and ungulates, this is combined with an underabundance of triadic trees. Additional results also confirmed that dominance relations tend to be transitive (Extended Data Fig. 1).

In humans, dominance hierarchies are observable from infancy. Nonetheless, the way dominance is expressed and evaluated changes during childhood. For example, the tendency to favor subordinate individuals when allocating resources increases over the kindergarten years<sup>55–58</sup>. Thus, we ran an additional analysis to evaluate the effect of age on human children's data. This complementary analysis showed no detectable effect of age on the overrepresentation of triadic pyramids in children dominance hierarchies (see Supplementary Analysis).

Study 1<sub>b</sub> used the same data as Study 1<sub>a</sub> to evaluate whether dominance hierarchies' triadic pyramidal motif is associated with shared evolutionary history. We used Bayesian models to assess the effect of group size and phylogeny on the triadic pyramidal metric (see Methods). One analysis focused on primates, including human children (36 species, 100 groups; Extended Data Fig. 2), and another focused on all species in our dataset (110 species, 311 groups; Extended Data Fig. 3).

For each analysis, the triadic pyramidal metric was the dependent variable. We assessed model fit using the deviance information criterion (DIC). A tested model is

considered a better fit when its DIC is smaller by a value of three or more than the reference null model<sup>59</sup>. Our analyses compared tested models including phylogeny or network size with a reference null model including only species as the random effect.

For the primate-only analysis, neither the model including phylogeny nor the one including network size outperformed the null model ( $\Delta\text{DIC} = -.78$  and  $\Delta\text{DIC} = 1.47$ ). For the all-species analysis, the model including phylogeny was a worse fit than the null model ( $\Delta\text{DIC} = 14.62$ ), and the model including network size did not improve upon the null model ( $\Delta\text{DIC} = 1.03$ ). Thus, the triadic pyramidal motif of dominance hierarchies is a widespread phenomenon, and is not noticeably affected by group size or phylogenetic history.

We verified the results of these analyses with Pagel's  $\lambda$ , a measure of phylogenetic signal that varies between 0 —phylogenetic independence— and 1 — traits covary in direct proportion to species' shared evolutionary history<sup>60</sup>. Pagel's  $\lambda$  estimates were close to zero both for the primate-only analysis ( $M = .096$ , mode = .018, 95% credible interval: .006–.293), and for the all-species analysis ( $M = .184$ , mode = .094, 95% credible interval: .011–.408).

### **Adults' expectations about the shape of hierarchies**

Next, Studies 2–4 investigated whether human adults draw inferences consistent with the pyramidal motif identified in Studies 1<sub>ab</sub>. During the learning phase, participants memorized a network of social relations that included dominance and symmetric relationships (friendship in Studies 2-3; enmity in Study 4). We introduced symmetric relationships to promote participants' generalization of dominance relationships across individuals. Friendships are more likely to occur between individuals of similar social standing<sup>61</sup>. Moreover, ally networks are often organized hierarchically, and groups frequently dominate other groups<sup>37,62</sup>. Thus, dominance relations are more likely to generalize between individuals bound by a symmetric relationship such as friendship, than between unrelated individuals.

Participants learned the relations one by one by receiving feedback on their answers to questions about the agents’ relations (Fig. 3, agents’ gender was counterbalanced across participants). The learning phase ended once the participants reached a learning criterion (see Methods). During the test phase, participants had to infer novel dominance relations between individuals in the network. Participants received no feedback on the accuracy of their answers during this phase. We analyzed inferences regarding novel dominance relations to determine whether they were consistent with a pyramidal motif.

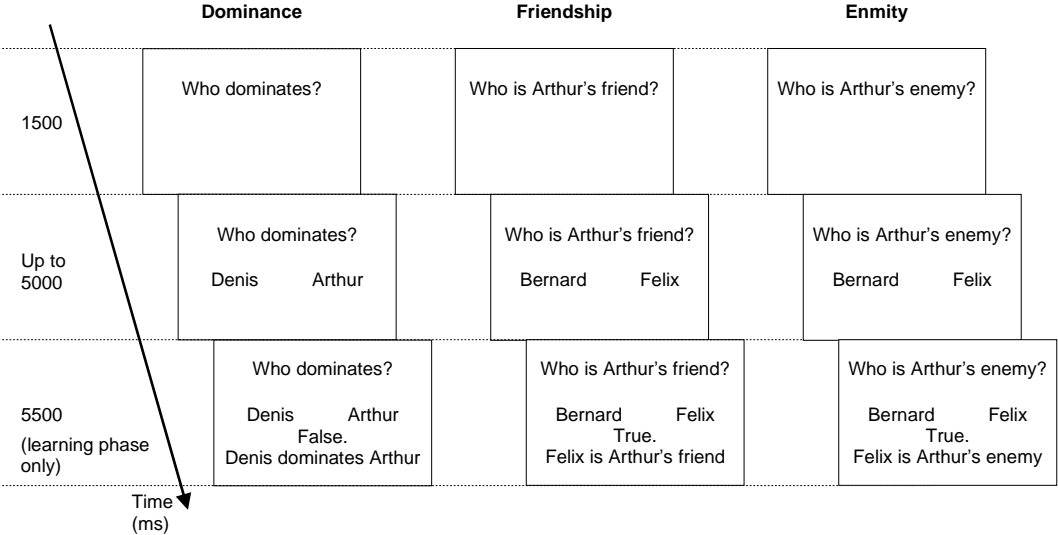


Figure 3. Timeline of trials testing adults on dominance, friendship, or enmity relations. Each question was presented alone for 1.5 s. Next, two names appeared, and the participant had 5 s to choose one. During the learning phase, participants received feedback on the accuracy of their answers for 5.5 s.

In two pilot studies (Studies S1<sub>ab</sub>, see Supplementary Methods and Results), we ensured that participants drew systematic inferences about novel dominance relations by generalizing dominance across friendships (e.g., after learning that A dominated B, subjects inferred that A’s friend dominated B’s friend). In Studies 2–3, we investigated whether those inferences were consistent with a pyramidal shape. We compared inferences compatible with a triadic pyramid (pyramid condition) with inferences compatible with a triadic tree (tree

condition) (Fig. 4). For instance, we tested pyramidal inferences based on the assumption that for each known dominance relation, the dominant would dominate their subordinate’s friends. We also tested tree-based inferences based on the assumption that for each known dominance relation, a subordinate would be dominated by their dominant’s friend.

In Studies 2–4, inference scores (proportion of correctly inferred test trials) were calculated to assess participant performance. For each experiment with adults (Studies 2–4), we ran a full-factorial ANOVA on inference scores with the following factors: condition (pyramid vs. tree; within-subject in Study 2, between-subject in Studies 3–4), gender of names (female vs. male; between-subject), and phrasing used to convey dominance (Study 2 only: A dominates B vs. B is dominated by A; between-subject). These analyses were followed by one-sample t-tests comparing average inference scores to chance (0.5, see detailed statistics in Table S4).

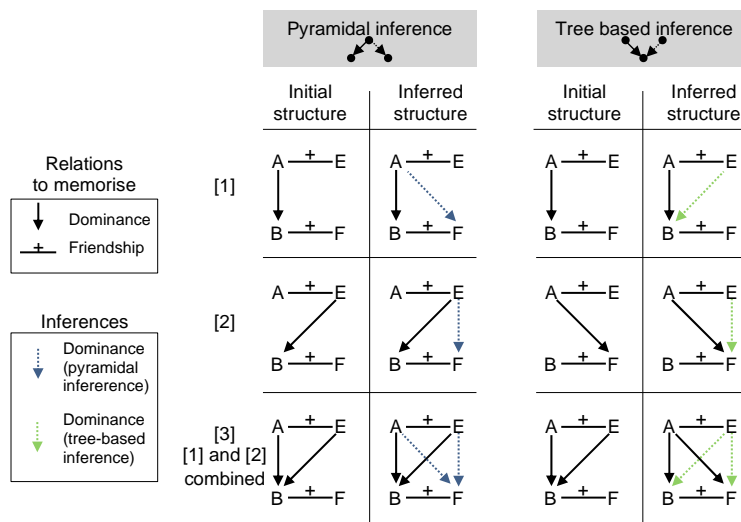


Figure 4. Examples of pyramidal and tree-based inferences. Each arrow represents a dominance relationship (pointing towards the subordinate agent). Line segments with a “+” on top represent friendships. Solid lines represent relations that participants had to memorize during the learning phase. Dotted lines represent novel dominance relations that can be inferred. [1] and [2] show examples of inferences tested in Study 2. A pyramidal inference is drawn when dominance is generalized following a triadic pyramidal pattern (one dominant individual and two subordinate individuals). A tree-based inference is drawn when dominance is generalized following a triadic tree pattern (one subordinate and two

dominants). [3] shows examples of inferences tested in Study 3, which combines inferences illustrated in [1] and [2].

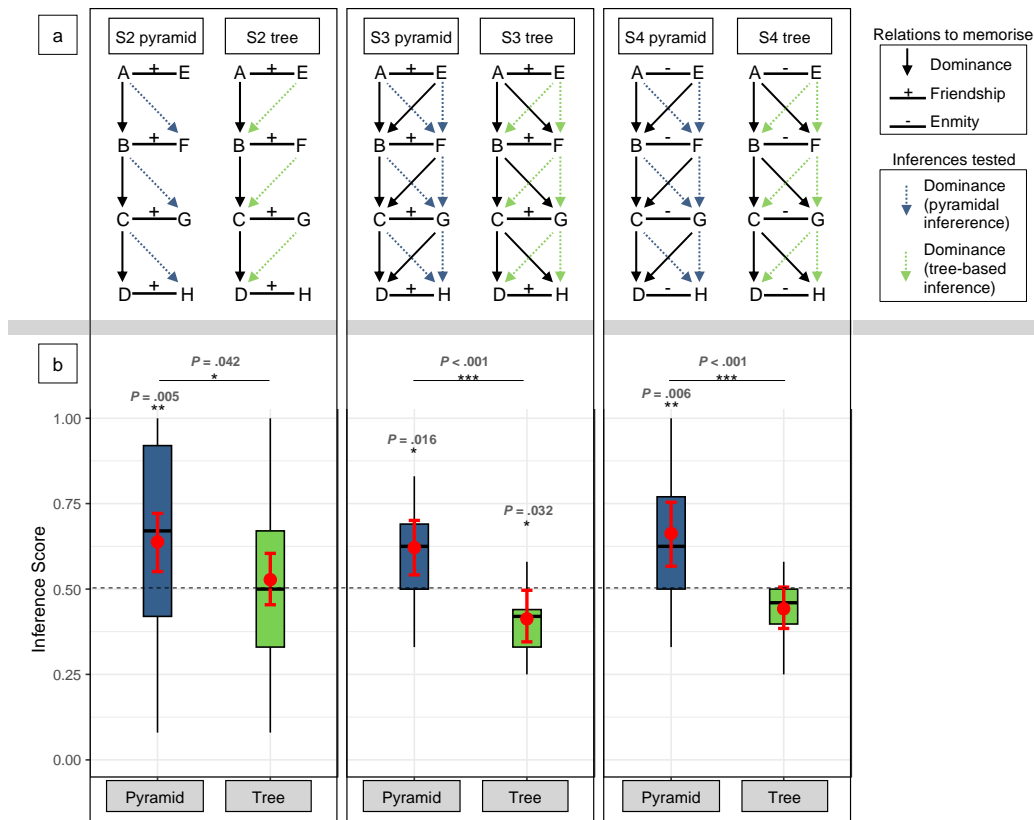


Figure 5. Network structures and results of Studies 2–4. a. Schematic representation of social networks used in Studies 2–4, per condition (Pyramid vs. Tree). Each arrow represents a dominance relation (pointing towards the subordinate agent). Lines represent friendships (“+” on top) or enmity relations (“-” on top). Solid lines represent relations that participants memorized during the learning phase. Dotted lines represent novel relations for inference during the test phase, with arrow direction representing a correct answer when computing inference scores. Note that participants never saw these graphical representations of social networks; they received information about relations one by one in a written format (see Figure 3). b. Inference scores across Studies 2–4 ( $n = 40/\text{study}$ ). Red dots and error bars indicate means and bootstrapped 95% CIs; horizontal bars within boxes indicate medians, and boxes indicate the middle two quartiles; upper whiskers represent data up to 1.5 times the interquartile range above the third quartile, and lower whiskers represent data up to 1.5 times the interquartile range below the first quartile; grey dots are individual data points. The effect of condition (pyramid vs. tree) on inference scores was assessed with two-tailed full-factorial ANOVAs on inference scores with the following factors: condition (pyramid vs. tree; within-subject in Study 2, between-subject in Studies 3–4), gender of names (female vs. male; between-subject), and phrasing used to convey dominance (Study 2 only: A dominates B vs. B is dominated by A; between-subject). For each Study,  $p$  values for comparisons of inferences scores against chance were assessed with two-tailed one-sample  $t$ -tests and were corrected for multiple comparisons across conditions using the Holm-Bonferroni procedure. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ .

In Study 2, inference scores were significantly higher in the pyramid condition than in the tree condition (ANOVA,  $F_{1,36} = 4.45$ ,  $p = .042$ ,  $\eta^2_p = .11$ , 95%CI = [.02, 1]). Other effects revealed by the ANOVA ran on Study 2's data are detailed in Supplementary Methods and Results. Inference scores were significantly higher than predicted by chance in the pyramid condition ( $t_{39} = 3.24$ ,  $p = .005$ ,  $d = .51$ , 95%CI = [.19, .96]), but not in the tree condition ( $t_{39} = .68$ ,  $p = .498$ ,  $d = .11$ , 95%CI = [-.20, .42]) (Fig. 5b). Thus, participants inferred novel dominance relations following a triadic pyramid and not a triadic tree.

While Study 2 tested the most likely inferences given the same initial social structure, Study 3 examined whether drawing pyramidal or tree-based inferences would cause participants to preferentially infer a given social structure. Study 3 was identical to Study 2, with a few exceptions (see Methods section). Crucially, in Study 3, the final structure in the test phase was identical across conditions (Fig. 5a), whereas the initial structure in the learning phase differed across conditions. Initial structures were designed so that final structures could be inferred through pyramidal inferences in the pyramid condition and tree-based inferences in the tree condition (Fig. 4[3]).

For Study 3, inference scores were significantly higher in the pyramid condition than in the tree condition (ANOVA,  $F_{1,36} = 13.99$ ,  $p < .001$ ,  $\eta^2_p = .28$ , 95%CI = [.09, 1]), and the ANOVA revealed no other significant effects. Inference scores were significantly higher than those predicted by chance in the pyramid condition (Fig. 5b,  $t_{19} = 2.95$ ,  $p = .016$ ,  $d = .66$ , 95%CI = [.27, 1.11]) and significantly lower than chance in the tree condition ( $t_{19} = -2.31$ ,  $p = .032$ ,  $d = -.52$ , 95%CI = [-1.43, -.03]). Thus, Study 3 confirmed that adults prioritize pyramidal inferences over tree-based inferences.

Study 4 assessed whether pyramidal inferences could be used to generalize dominance relations across enmity social relations. Similar to friendship, enmity relationships cue some proximity in dominance, because they imply that enemies are engaged in an unresolved

conflict, and can thwart each other's goals<sup>63</sup>. Thus, enmity relations are less likely to occur between individuals that are far apart in dominance status than between those that are close in dominance status.

Study 4 was identical to Study 3, except that friendships were replaced with enmity relations (Fig. 5a). The results of Study 4 confirmed those of Study 3. Again, inference scores were significantly higher in the pyramid condition than in the tree condition (ANOVA,  $F_{1,36} = 14.51$ ,  $p < .001$ ,  $\eta^2_p = .29$ , 95% CI = [.1, 1]), and no other significant effects beside condition were revealed by the ANOVA. Additionally, inference scores were significantly higher than those predicted by chance in the pyramid condition (Fig. 5b,  $t_{19} = 3.43$ ,  $p = .006$ ,  $d = .77$ , 95% CI = [.44, 1.25]) but not in the tree condition ( $t_{19} = -1.80$ ,  $p = .088$ ,  $d = -.40$ , 95% CI = [-.97, .04]). Thus, Studies 3–4 indicated that humans generalized dominance relations in accordance with a pyramidal pattern across two distinct types of symmetric relations (friendship and enmity). Participants systematically drew pyramidal inferences about dominance, but not comparable tree-based inferences.

### **Infants' expectations about the shape of hierarchies**

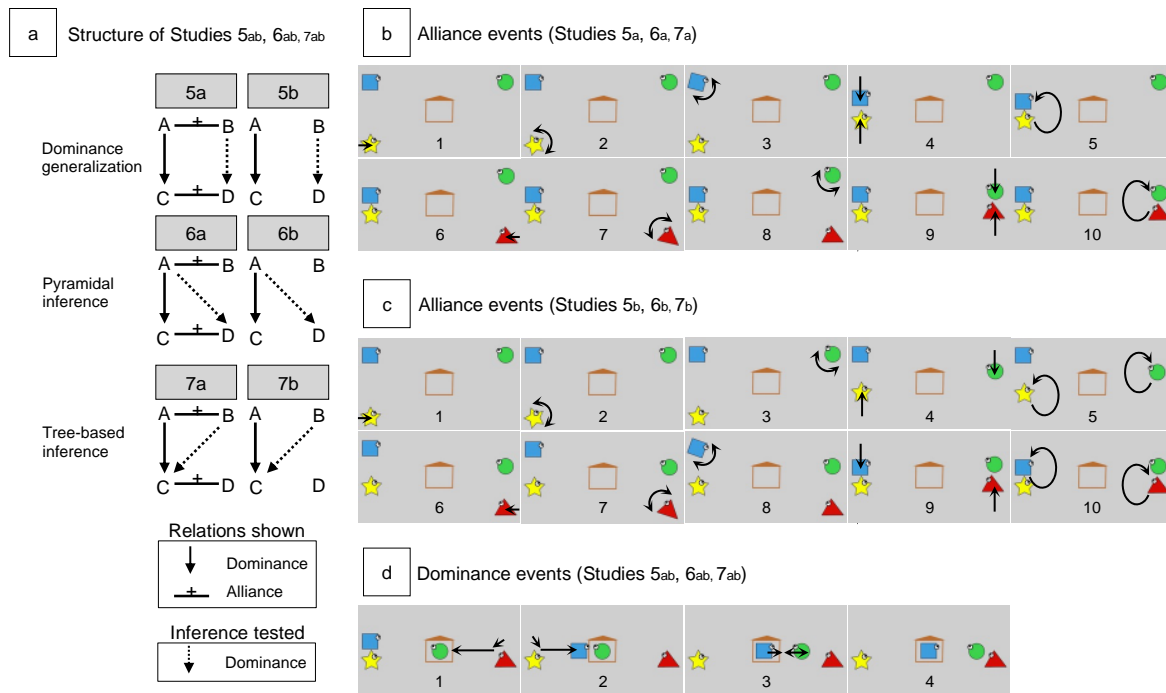
Studies 2–4 showed that human adults draw inferences consistent with the triadic pyramidal shape of dominance structures. The subsequent experiments (Studies 5<sub>ab</sub>-6<sub>ab</sub>-7<sub>ab</sub>) tested human infants. Their goal was to investigate whether expectations about the pyramidal shape of hierarchies are intuitive and emerge in the absence of formal training. The work capitalizes on previous research on infants' capacity to extract information about social relations<sup>44,46,64-84</sup>.

In Studies 5<sub>ab</sub>-6<sub>ab</sub>-7<sub>ab</sub>, we used looking-time to test infant inferences of novel dominance relations, building on the well-known tendency of infants to look longer at events that they find unexpected or hard to process<sup>85,86</sup>. We tested 14-month-old infants because by this age infants' capacity to process information about dominance<sup>44,66,68,69,73,75</sup> and alliance<sup>78-</sup>

<sup>81,83,84</sup> relations is well-established. We familiarized infants with movies designed to convey information about a set of relations between four schematic agents (A, B, C, D), which were represented by 2D geometrical shapes with eyes, similar to many studies on social cognition in infants<sup>46,66,71,73–75,80,87–90</sup>. During the test phase, we assessed infants' expectations of an unobserved dominance interaction. Studies 5<sub>ab</sub> tested whether infants generalized dominance across allies. Studies 6<sub>ab</sub>-7<sub>ab</sub> tested whether their generalizations were consistent with the pyramidal motif observed in dominance networks (Fig. 6a).

In Studies 5<sub>a</sub>-6<sub>a</sub>-7<sub>a</sub>, infants were familiarized with events designed to convey that A and B were allies, C and D were allies, and A dominated C (see Methods; Movie S1). Allies took turns reacting to each other, approached, moved together along the same path, and stayed in close spatial proximity (Fig. 6b). Next, one member per pair competed to occupy a small marked area at the center of the screen (Fig. 6d). One of the competing agents eventually succeeded in monopolizing access to the area (henceforth the dominant), pushing away the other agent (henceforth the subordinate).

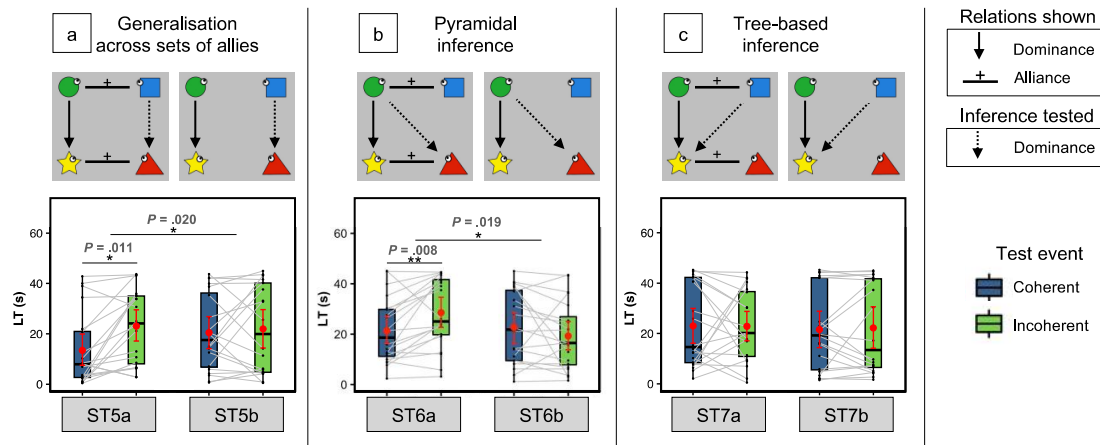
Next, infants saw two test videos assessing their inferences about the dominance relations between two agents that were not shown to compete. Identities of the competing agents varied across experiments. For instance, because Study 5<sub>a</sub> tested capacity to generalize dominance across sets of allies, Study 5<sub>a</sub>'s test videos showed the dominant agent's ally competing against the subordinate agent's ally. The dominant's ally prevailed in the coherent events, whereas the subordinate's ally prevailed in the incoherent events (Movie S2). Once the competition ended, the screen froze and we measured looking-time. For Study 5<sub>a</sub>, infants are predicted to expect the dominant's ally to prevail over the subordinate's ally, and thus, to look longer at the incoherent events.



*Figure 6. Network structures and events used in Studies 5<sub>ab</sub>-6<sub>ab</sub>-7<sub>ab</sub>. a. Schematic representation of social networks used in Studies 5<sub>ab</sub>-6<sub>ab</sub>-7<sub>ab</sub>. Each arrow represents a dominance relation (pointing towards the subordinate agent). Lines represent alliances (“+” on top). Solid lines represent relations observed during familiarization videos. Dotted lines represent relations assessed during the test phase, with arrow directions representing the correct answer when computing inference scores. b. Stills of videos conveying information about alliances in Studies 5<sub>a</sub>-6<sub>a</sub>-7<sub>a</sub>. c. Stills of videos conveying information about alliance in Studies 5<sub>b</sub>-6<sub>b</sub>-7<sub>b</sub>. d. Stills of videos conveying information about dominance in Studies 5<sub>ab</sub>-6<sub>ab</sub>-7<sub>ab</sub>.*

As controls for Studies 5<sub>a</sub>-6<sub>a</sub>-7<sub>a</sub>, Studies 5<sub>b</sub>-6<sub>b</sub>-7<sub>b</sub> tested the role of alliances in guiding how infants generalized dominance relations. Controls were identical to their respective studies, except that alliance information was made more ambiguous by changing the timing of actions (Movies S3–4, Figure 6c). In the three controls, each agent responded to and moved along the same path as its partnered agent located on the opposite corner of the screen, but also approached the agent on the same side of the screen and remained in close proximity. Thus, the control familiarization video did not convey that there were two distinct groups of allies.

For each pair of these studies ( $5_{ab}$ ,  $6_{ab}$ ,  $7_{ab}$ ), we ran a two-way ANOVA on log-transformed looking-time. Independent variables were test coherence (coherent vs. incoherent; within-subject) and study ( $5_a$  vs.  $5_b$ ;  $6_a$  vs.  $6_b$ ;  $7_a$  vs.  $7_b$ ; between-subject). These analyses were followed by tests for matched pairs (see detailed statistics in Table S5).



*Figure 7. Looking-time (s) per situation (coherent vs. incoherent) and Study ( $n = 20$ /study). a. Studies  $5_{ab}$ . b. Studies  $6_{ab}$ . c. Studies  $7_{ab}$ . Red dots and error bars indicate means and bootstrapped 95% CIs; horizontal bars within boxes indicate medians, and boxes indicate the middle two quartiles; upper whiskers represent data up to 1.5 times the interquartile range above the third quartile, and lower whiskers represent data up to 1.5 times the interquartile range below the first quartile; grey dots are individual data points; grey lines connect repeated measures from individuals. Interactions between coherence and study were assessed with full factorial two-tailed ANOVAs on log-transformed looking-time with test coherence (coherent vs. incoherent) as a within-subject variable and study ( $5_a$  vs.  $5_b$ ;  $6_a$  vs.  $6_b$ ;  $7_a$  vs.  $7_b$ ) as a between-subject variable. For each study,  $p$  values for the effect of coherence on looking-time were assessed with two-tailed  $t$ -tests for matched pairs, and were corrected for multiple comparisons across pairs of Studies (Studies  $5_{ab}$ ,  $6_{ab}$ ,  $7_{ab}$ ) using the Holm-Bonferroni procedure  $*p < .05$ ,  $**p < .01$ ,  $***p < .001$ .*

In Studies  $5_{ab}$ , infants looked longer at incoherent than coherent test events (ANOVA,  $F_{1,38} = 4.80$ ,  $p = .035$ ,  $\eta^2_p = .11$ , 95% CI = [0, 1]). The interaction between coherence and study was also significant ( $F_{1,38} = 5.93$ ,  $p = .020$ ,  $\eta^2_p = .13$ , 95% CI = [.01, 1]), revealing that infants responded to situations differently, depending on the study. Infants in Study  $5_a$  looked significantly longer at incoherent test events than at the coherent ones (Fig. 7a,  $t_{19} = -3.12$ ,  $p = .011$ ,  $d = -.70$ , 95% CI = [-1.11, -.35]), implying that they expected the dominant's ally to

prevail over the subordinate's ally. Conversely, infants in Study 5<sub>b</sub> did not differ in looking-time between incoherent and coherent events, as expected when alliances were ambiguous (Fig. 7a,  $t_{19} = .180$ ,  $p = .858$ ,  $d = .04$ , 95% CI = [-.46, .48]). Thus, information about alliances shaped infants' generalization of dominance relations across individuals.

Next, Studies 6<sub>ab</sub> investigated whether infant inferences in Studies 5<sub>ab</sub> were consistent with a triadic pyramidal motif (Fig. 6a). These studies followed the same procedures as Studies 5<sub>ab</sub>, except that in the test videos of Studies 6<sub>ab</sub>, the dominant agent competed with the subordinate's ally (Movie S5). The dominant agent prevailed in the coherent test, whereas the ally of the subordinate agent prevailed in the incoherent test. Thus, Study 6<sub>ab</sub> tested whether infants generalize dominance according to a triadic pyramidal pattern.

In Studies 6<sub>ab</sub>, the interaction between test coherence and study was significant (ANOVA,  $F_{1,38} = 6.03$ ,  $p = .019$ ,  $\eta^2_p = .14$ , 95% CI = [.01, 1]). Thus, infants responded differently to events depending on the study. In Study 6<sub>a</sub>, infants looked significantly longer at incoherent than at coherent test events (Fig. 7b,  $t_{19} = -3.29$ ,  $p = .008$ ,  $d = -.74$ , 95% CI = [-.87, -.29]), indicating an expectation that the dominant agent will prevail over the ally of its subordinates (pyramidal inference). Additionally, test coherence had no detectable effect on looking-time in Study 6<sub>b</sub> (Fig. 7b,  $t_{19} = .99$ ,  $p = .334$ ,  $d = .22$ , 95% CI = [-.08, .72]), confirming the role of alliances in guiding infant generalization of dominance relations.

We then tested whether infants drew comparable inferences when the resulting network was tree-like in Studies 7<sub>ab</sub> (Fig. 6a). While generally following the same procedures as Studies 6<sub>ab</sub>, Studies 7<sub>ab</sub> differed in showing test videos with the subordinate competing against the dominant's ally (Movie S6). The subordinate agent prevailed in the incoherent events and yielded in the coherent events. If infants expect pyramidal social hierarchies, they should not make inferences that accord with a triadic tree. Thus, we expected null findings in Studies 7<sub>ab</sub>. As predicted, the two-way ANOVA revealed no significant effects. Moreover,

follow-up analyses revealed no significant effect test coherence on infants looking-time (Fig. 7c, Table S5). Thus, infants showed no detectable tendency to draw tree-based inferences about dominance relationships.

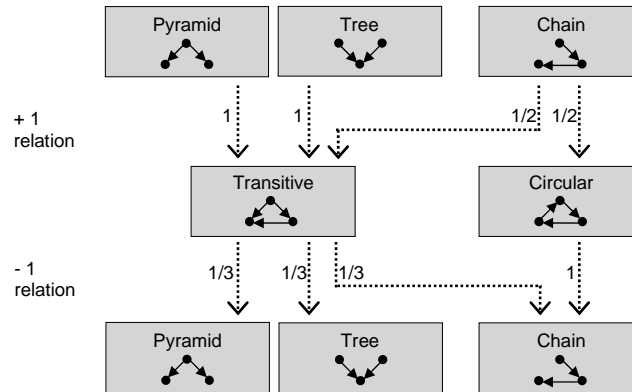
## Discussion

Our studies demonstrated that dominance structures exhibit a triadic pyramidal motif across a wide range of species (including humans) with very different cognitive abilities, ecologies, and social environments. Moreover, the overrepresentation of pyramidal triads is widespread, and relatively independent of group size and phylogeny. This structural pattern is understandable when considering that dominance relationships plausibly regulate costs associated with resource competition<sup>10–12,18,19</sup>.

Study 1<sub>a</sub> confirms that transitive triads are also overrepresented in dominance hierarchies (Extended Data Fig. 1), in line with the literature<sup>8,14,20</sup>. Note that the overrepresentation of triadic pyramids and that of transitive structures are not opposing phenomena. Instead, they correspond to two distinct cases: pyramids are predominant for triads with two relationships, while transitive structures are predominant for triads with three relationships. Further, both phenomena are consistent with the hypothesis that social dominance serves to regulate the costs associated with competition for resources. Among the possible triadic structures, pyramids and transitive triads better regulate conflict over resources than comparable equivalent structures (Fig. 1).

There is also some complementarity between pyramidal and transitive triads. Indeed, a high frequency of triadic pyramids may contribute to the emergence of transitive structures. As Fig. 8 shows, when a third relation is added to a triadic pyramid, the resulting structure is necessarily transitive<sup>91,92</sup>. Note, however, that the overrepresentation of triadic pyramids relative to trees cannot be explained by their likelihood to turn into transitive structures.

Actually, the probabilities of transforming a pyramid or a tree into a transitive structure by adding a third relation are identical (Fig. 8).



*Figure 8. Transition probability graph for triadic structures with two or three relations. Numbers next to arrows represent the transitional probabilities for transforming one structure into another. We consider two cases: adding a relation with a randomly-chosen direction (+1 relation), and randomly deleting one relation in the structure (-1 relation). Triadic pyramids and trees stand in comparable relations with transitive structures in this graph. When a third relation is added to a triadic pyramid or to a triadic tree, the resulting structure is necessarily transitive ( $p = 1$ ), irrespective of whether the relation goes from left to right, or from right to left. Moreover, randomly pruning one relation from a triadic transitive structure is equally likely to yield a pyramid or a tree ( $p = 1/3$  in both cases).*

The triadic pyramidal motif of dominance hierarchies opens up many questions about the proximal mechanisms supporting its emergence. The same structural regularity can be underpinned by a wide variety of proximal mechanisms, which sometimes differ across species and environments. For instance, dominance transitivity can emerge through individual and social attributes, spatial organization, social dynamics, or social learning<sup>14</sup>. The overrepresentation of triadic pyramids in hierarchies, just like dominance transitivity, might result from several proximal mechanisms. Our hypothesis predicts an overrepresentation of pyramids compared to triadic trees. Structurally, this hypothesis can be implemented in two non-mutually exclusive ways. Triadic pyramids might be (i) more stable than trees and (ii) more likely to emerge. Each of these two structural phenomena can result from a variety of proximal factors.

For example, triadic pyramids might be more stable than triadic trees as a result of simple social dynamics. In a triadic tree, two individuals occupy the top position and have the same priority of resource access, creating an opportunity for conflicts to arise between the two dominant individuals whenever resources can be monopolized. This may eventually result in instability because these conflicts can generate novel dominance relations that alter the hierarchical structure. In contrast, a triadic pyramid involves one dominant individual that can monopolize resources, leaving fewer opportunities for conflicts between subordinates, thus making triadic pyramids comparatively more stable than triadic trees.

Similarly, several mechanisms could make triadic pyramids more likely to emerge than triadic trees, and one of these may be the result of individual attributes. For instance, if there is a correlation between individuals' competitive ability and aggression, dominant individuals might be more likely to engage in contests than lower-ranked individuals, thus making triadic pyramids more likely to appear than triadic trees. Moreover, we observed that humans (adults and infants) draw inferences consistent with the triadic pyramidal shape of hierarchies. Thus, in humans, social learning by bystanders could make triadic pyramids more likely to emerge than triadic trees. In short, the study of the set of proximal mechanisms supporting the emergence of triadic pyramidal hierarchies is very much open, making for an important question of future research.

If human expectations about the shape of dominance structures are generally accurate, they should be consistent with the triadic pyramidal motif of hierarchies. Previous studies have robustly demonstrated that human adults and infants expect dominance relations to be transitive and infer novel relations accordingly<sup>44,46,48,49</sup>. We find that humans also draw comparable inferences based on a pyramidal shape. Human adults inferred novel dominance relations when they were consistent with a triadic pyramid, but not when they were consistent with a triadic tree (Studies 2–4). These results are all the more remarkable given that triadic

pyramids and triadic trees have identical elements and equivalent complexity. Research suggests that adults find hierarchies easy to process<sup>49,93</sup> and that they can rapidly determine dominance relations between individuals<sup>94,95</sup> or groups<sup>96</sup>. Our data demonstrate how expectations about pyramidal structures contribute to the speed and efficiency of processing dominance relations.

Like logical inferences, the pyramidal inferences that we observed rely on a sensitivity to the structural organization of multiple relations. Indeed, participants' inferences were shaped by the organization of relations within networks in Studies 2-4. Relying on formal structural regularities allows learners to infer outcomes across a wide variety of situations, independent of how social relations are expressed behaviorally<sup>34,97,98</sup>. However, pyramidal inferences in our experiments exhibit an important departure from logical inferences. In classic logic, inferences are necessary: if the premises supporting an inference are true, then the conclusion is necessarily true. In contrast, the pyramidal inferences that we studied appear probabilistic (i.e., if A dominates B, and B is a friend of C, then it is likely that A dominates C, but not necessarily).

Children form dominance relationships<sup>99</sup> and dominance hierarchies<sup>100-102</sup> before two years of age. Our data indicate that by 14 months of age, humans have expectations about the pyramidal shape of hierarchies. In our Studies, infants successfully generalized dominance relations across sets of allies (Studies 5<sub>ab</sub>), making inferences consistent with a pyramidal shape (Studies 6<sub>ab</sub>) and not with a tree-like shape (Studies 7<sub>ab</sub>). Moreover, information about alliances was crucial to these inferences, as the infants showed no tendency to infer novel dominance relations when alliances were ambiguous. Our results thus dovetail with studies showing that infants combine information from two distinct relational domains: alliances and dominance<sup>70,71</sup>.

Discovering the structure of dominance hierarchies poses substantial cognitive challenges for individuals within them because structural regularities are unlikely to be observed directly. Instead, a learner typically witnesses interactions between individuals that are then used to infer social relations which are themselves organized into structures. Moreover, relationship networks can theoretically form a very large number of shapes. Thus, discovering structural form requires navigating a vast hypothesis space<sup>103,104</sup>. Our data indicate that expectations about the pyramidal shape of dominance hierarchy guide the navigation of social structures from infancy and onwards, emerging spontaneously in humans without formal training or explicit teaching. Importantly, our data do not allow us to determine whether the capacity to draw pyramidal inferences has ancient phylogenetic origins. Thus, testing whether animal species engage in pyramidal inferences comparable to those that we observed in humans is another important question for future research.

In conclusion, our data showed that the triadic pyramidal structure of dominance hierarchies is widespread across a wide range of species including humans, with little detectable influence of phylogeny. From infancy, humans form expectations about the triadic pyramidal shape of hierarchies, and rely on them to infer unobserved dominance relations. These results contribute to explain why pyramids are frequently used to organize hierarchies in human societies.

### **Methods**

This research was approved by an independent ethical committee (CPP Sud-Est II, IRB: 00009118). All adult participants and infants' caregivers gave their informed written consent prior to the inclusion of participants in the Studies (except for Study 1<sub>ab</sub>, which relied on data openly accessible from the literature). Adults enrolled in Studies 2-4 received 10€ as a compensation for their participation. Families enrolled in Studies 5<sub>ab</sub>-6<sub>ab</sub>-7<sub>ab</sub> received no

financial compensation but were given a “little scientist diploma” as a thank you gesture. The studies reported in this manuscript were not pre-registered.

### **Studies 1<sub>ab</sub>**

**Datasets.** Human data were obtained from a Google Scholar search performed during April 2021, using the following exact query: “*social dominance matrix children*”. We then screened for all studies that reported systematic data on randomly sampled, naturally occurring conflicts (physical attack, threat, or competition) between children in daycare centers (15 distinct groups). We also opportunistically added as many datasets as possible (5 additional distinct groups). Studies were included if they reported data that showed either who won each of the observed conflicts, or dominance relationships (i.e., which individual won more conflicts in a dyad). A priori, we planned to use only data collected at the first time point for articles reporting longitudinal data from the same group. However, none of the studies retained in our analysis reported longitudinal data on children’s dominance networks. The final dataset included dominance networks from 20 groups of children (see metadata in Table S6).

Animal data were obtained from DomArchive, a large database of agonistic interactions in multiple species<sup>50</sup>. We excluded networks in which all individuals were directly connected by dominance relations, because triadic pyramids and triadic trees cannot occur in such networks (80 networks). When repeated measurements were reported for the same group of animals, we kept only the first reported measure in the analysis (48 networks). Taxonomic categories were generated via grouping networks from orders with 16 networks or more: Primates (81 networks), Carnivora (38 networks), Rodentia (53 networks), Artiodactyla (38 networks), Passeriformes (29 networks), and Hymenoptera (17 networks). Animals

belonging to an order with fewer than 16 networks in our database were pooled together in the “other” category (50 networks).

**Preprocessing.** Raw interaction data on conflict outcome were used to create dominance matrices. For each dyad per group, the individual that won the majority of conflicts was considered dominant, while the other was considered subordinate. In dominance matrices, the dominant was assigned a row of 1, and the subordinate a row of 0. If two individuals won the same number of conflicts or were never observed interacting, each received 0 in their respective rows. For a subset of included studies, data were only available as dominance matrices (directly reporting which individual per dyad won most conflicts). In these cases, we directly extracted information from the dominance matrices.

We converted dominance matrices into dominance networks, where nodes represented individuals and edges represented directed dominance relationships. Each dominant-subordinate relationship in the matrix was considered an asymmetric dyad in the corresponding network. For each dominance network, we counted the frequency of the five triadic patterns with two or three asymmetric edges (triadic pyramid, triadic tree, chain, transitive, and circular patterns; see Fig. 1). Statistical analyses were based on the distribution of triadic patterns.

**Phylogenetic analyses.** In Study 1<sub>b</sub>, we used Bayesian phylogenetic models to estimate the effects of group size and relatedness on the triadic pyramidal metric. We used the 10k tree phylogeny to estimate relatedness among primates<sup>105</sup> and a consensus tree from the Open Tree of Life (v.13.14, <https://tree.opentreeoflife.org/about/synthesis-release/v13.4>) to estimate relatedness among all species. Species absent from these phylogenies were excluded from analyses for this experiment (Primates: *Cercocebus sanjei*; all species: *Sus scrofa*, *Pachycondyla*, *Elemur fulvus*, *Gorilla gorilla*, *Pan troglodytes*).

When necessary, the phylogeny was made ultrametric, using non-negative least squares<sup>106</sup>, then transformed into an inverted phylogenetic covariance matrix using the algorithm of Hadfield and Nakagawa<sup>107</sup>. This covariance matrix was added as a random effect in Bayesian phylogenetic mixed models, with triadic pyramidal metric as the dependent variable. We used uninformative priors ( $V = 1$ ,  $\nu = .002$ ; Hadfield, 2010) with 13,000 iterations and a burn-in of 3000.

Three models were compared: null (including only the random effect of species), phylogeny (including random effects of species and phylogeny), and group size (including random effect of species and fixed effect of group size).

### **Studies 2–4**

**Participants.** The analysis included 120 participants across Studies 2–4 ( $M_{age} = 22.88$  y; range = 18–34 y; 65 females,  $n = 40$ /study). The participants were recruited by sending announcement on several cognitive science mailing list distributed in the Lyon area, and by advertising the study on social media. All adult participants gave their informed written consent prior to their inclusion in the studies. The participants were randomly assigned to Studies and conditions. Pyramid and tree conditions were tested within subjects in Study 2 and between subjects in Studies 3–4. See Supplementary Methods and Results for details on sample-size justification, mean age and age range per condition and study, and participant exclusion.

**Materials and procedure.** Data were collected in France between March 2017 and June 2018. Participants were seated approximately 70 cm from a 19-inch LCD monitor and responded with an AZERTY keyboard. Stimuli were presented on the monitor using MATLAB R2015b and the Psychophysics Toolbox<sup>108</sup>. Experimenters were not blind to conditions, but they were not present in the testing room during the experiments. Before the

experiment, participants received instructions indicating that they would be learning about social relationships among eight individuals, and partook in a brief warm-up (see Supplementary Methods and Results). Next, participants were enrolled in the learning and test phases.

**Learning phase.** Participants memorized a set of social relations between individuals represented by first names (solid lines in Fig. 5a). During each trial, a question about dyadic social relations appeared on the screen (e.g., “Who dominates?” for dominance relations; “Who is [name]’s friend?” for friendships; “Who is [name]’s enemy?” for enmity). After a 1.5 s post-trial onset, two names appeared below the question, one on each side of the screen. Participants were instructed to select one of the two options within 5 s by pressing the keyboard’s right or left arrow. For dominance relations, participants chose between the names of a dominant individual and that of its subordinate. For friendship and enmity, participants chose between names of the friend or enemy of the individual in the question and a name randomly selected from other individuals in the structure. Timeouts were treated as incorrect answers. Immediately after a response or 5 s elapsed, feedback appeared on the screen for 5.5 s and the trial ended. Feedback indicated whether responses were “True” or “False,” and stated the correct answer (e.g., “[name 1] dominates [name 2]” for dominance, “[name 1] is [name 2]’s friend” for friendships, and “[name 1] is [name 2]’s enemy” for enmity). Trials were presented in blocks, with one trial per relation memorized for each block. Participants could take a brief break between blocks. The learning phase ended once participants correctly answered in all trials of a block.

**Test phase.** Participants answered questions about the relations memorized during the learning phase (filler trials) and about novel dominance relations (test trials). Filler and test trials were similar to learning-phase trials, except that participants did not receive feedback and there was no time limit. The test phase included two blocks, with one trial per relation in

each block (seven filler and six test trials in Study 2; 10 filler and six test trials in Studies 3-4, see Fig. 5a). For further details, see Supplementary Methods and Results.

### **Studies 5<sub>ab</sub>-6<sub>ab</sub>-7<sub>ab</sub>**

**Participants.** These experiments included 120 healthy, full-term, 14-month-old infants ( $M_{age} = 431$  d; range = 389–468 d; 58 females,  $n = 20$ /condition in each study). The infant participants were recruited by sending letters to a randomly selected sample of children born in two large French cities (Lyon and Paris). The parents of all participants gave their informed written consent prior to their inclusion in the studies. The participants were randomly assigned to Studies and conditions. See Supplementary Methods and Results for details on sample size justification, mean age and age range per condition and study, and participant exclusion.

**Materials and procedure.** Data were collected in France between February 2017 and March 2022. A hidden camera mounted above the screen recorded infants' looking behavior. Caregivers were instructed to close their eyes to avoid caregiver interference. Apart from the infants' caregiver, and the infants themselves, no one else was present in the testing room during the experiment. Experimenters were not blinded to conditions, but monitored the experiment from a separate room. During the experiment, infants watched 2D animations generated with Synfig Studio (v.1.0). These animations involved four geometrical figures with eyes (representing agents): a blue square, green circle, red triangle, and yellow star. At the center of the screen, brown lines and a triangle formed a marked area shaped like a house. The marked area could hold only a single agent.

In Studies 5<sub>a</sub>.6<sub>a</sub>.7<sub>a</sub>, infants first saw four 7 s warm-up videos showing each of the agents alone, moving towards the center of the marked area, and staying there motionless for

2 s; this conveyed the agents' aim of occupying the marked area. Next, four familiarization videos showed interactions between the agents (named here A, B, C, and D), which were designed to convey that A and B were allies, C and D were allies, and A dominated C. The videos used cues validated in previous studies<sup>46,66,68,80,81,109,110</sup>. Long (22 s) and short (13 s) versions of the familiarization videos were used to alleviate boredom (Movie S7). In the long familiarization videos, alliances were conveyed by showing pairs of agents taking turns to oscillate and emit sounds (responding to each other), approaching each other, moving together along the same circular path, and staying next to each other (Fig. 6b).

Dominance relations were conveyed by showing two agents competing to occupy the marked area at the center of the screen (Fig. 6d). The dominant agent succeeded in pushing out the subordinate agent and occupying the marked area thrice in each familiarization video. Short familiarization videos were identical to long ones, except that agents did not move together along a circular path. Familiarization videos were shown in the following order: long, short, short, long. Next, infants saw two test movies probing their inferences about a novel dominance relation.

Test movies were identical to the short familiarization videos, except for the identity of the two competing agents. In Study 5<sub>a</sub>, the dominant's ally competed with the subordinate's ally. In Study 6<sub>a</sub>, the dominant competed with the subordinate's ally. In Study 7<sub>a</sub>, the subordinate competed with the dominant's ally. In movies showing coherent test events, the dominant agent or its ally prevailed. In movies showing incoherent test events, the subordinate agent or its ally prevailed. Once the competitive interaction was over, the screen froze and we measured looking-time up to the point infants looked away for > 2 s, or after 45 s had elapsed since the measurement began. Each participant saw a coherent and incoherent test event (order of presentation was counterbalanced across participants). We counterbalanced across participants whether each given test movie was used as a coherent test

event or as an incoherent test event, thus controlling for any effect of agents' shapes on infant behaviors during the test phase (see details about counterbalanced factors in Supplementary Methods and Results).

Studies 6<sub>b</sub>-7<sub>b</sub>-8<sub>b</sub> were identical to Studies 6<sub>a</sub>-7<sub>a</sub>-8<sub>a</sub> (respectively), except that we made information about alliances ambiguous by modifying the order of the agents' movements (Fig. 6c). Each agent interacted with the agent located at the opposite corner of the screen by taking turns to oscillate and emit sounds, then moving together along the opposite circular path. However, each agent also approached and stayed next to the agent located on its own side of the screen. When reporting the results of Studies 6<sub>b</sub>-7<sub>b</sub>-8<sub>b</sub>, we labelled "coherent" the test events where the dominant agent or the agent located on the dominant agent's side prevailed; we labelled "incoherent" the test events where the other agents prevailed. See Supplementary Methods and Results for additional details regarding procedures and coding.

**Analysis.** Data were preprocessed and analyzed with R (v.4.1.0) and R studio (v.1.4.1717), using the following packages: tidyverse (v.2.0.0), rcompanion (v.2.4.1), rstatix (v.0.7.2), afex (v.1.0.1), rotl (v.3.0.12), datelife (v.0.6.1), MCMCglmm (v.2.33), phytools (v.1.0.3), phylobase (v.0.8.10), and phylosignal (v.1.3). All significance tests were two-tailed, and p-values were corrected for multiple comparisons using the Holm-Bonferroni procedure. All 95% CIs reported were bootstrapped using 1000 samples. To better approximate a normal distribution, infant looking time data were log-transformed<sup>111</sup>. However, descriptive statistics and plots feature untransformed looking time data to ease interpretation.

### **Data availability**

All data are available at <https://doi.org/10.17605/OSF.IO/PK7BG>

### **Code availability**

All analysis scripts are available at <https://doi.org/10.17605/OSF.IO/PK7BG>

### **Acknowledgements**

We thank the participants and their parents, M. Brun and A. Couderc for their help with data collection and coding, as well as all the members of L2C2 and INCC for their invaluable inputs at all stages of this research. This work was supported by an ANR Fellowship to O.M. (Foundtrust, ANR-21-CE28-0017). The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

### **Author contributions statement**

O.M. supervised the project. O.M., N.C. designed the network data analysis. O.M., A.D. gathered children's network data from the literature. N.C. implemented the network data analysis. O.M., N.G., H.P., J.B.V.H. designed the experimental studies. N.G., H.P. created the experimental materials. N.G., H.P., A.D. collected and coded the experimental data. O.M. wrote the analysis script for experimental data. O.M. wrote the original draft. O.M., N.G., H.P., A.D., J.B.V.H., N.C. reviewed and edited the manuscript.

### **Competing interests statement**

The authors declare no competing interest.

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## Supplementary Materials

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## Supplementary Analysis

### Analysis of the effect of age on the structure of children's hierarchies

In a complementary analysis, we assessed the effect of age on our results. First, we ran a linear regression with the triadic pyramidal metric as the outcome variable, and age (in months, mean-centered) as a continuous variable. This analysis revealed no effect of age (unstandardized B coefficient [ $B$ ] = -.001, standardized  $\beta$ -coefficient [ $\beta$ ] = -.17, 95% CI = [-.67, .33],  $SE = .24$ ,  $p = .473$ ). To investigate further the effect of age, we used a median-split to separate groups of younger participants ( $M_{average-age} = 29.03$  months, average-age range = 13–49 months, 11 groups, 137 individuals) from groups of older participants ( $M_{average-age} = 61.48$  months, average-age range = 51–74 months, 9 groups, 140 individuals). We ran a linear regression with the triadic pyramidal metric as the outcome variable, and age as a categorical variable (younger vs. older). This analysis revealed no effect of age on the triadic pyramidal metric ( $M_{younger} = .67$  vs.  $M_{older} = .63$ ,  $B = -.04$ ,  $\beta = -.34$ , 95% CI = [-1.29, .62],  $SE = .45$ ,  $p = .467$ ).

Next, we analyzed separately data from the younger and older groups resulting from the median-split by age. The average triadic pyramidal metric was significantly higher than predicted by chance in both age groups (respectively  $M_{younger} = .67$ ,  $W_+ = 62$ ,  $p_{corr} = .008$ ,  $r = .78$ , 95% CI = [.46, .89] for younger participants, and  $M_{older} = .63$ ,  $W_+ = 45$ ,  $p_{corr} = .008$ ,  $r = .89$ , 95% CI = [.89, .90] for older participants, Holm-Bonferroni corrected p-values). Thus, triadic pyramids were over-represented in dominance networks in younger and older participants alike.

Subsequent analyses focused on normalized z-scores, computed as reported in the main text. Average normalized z-scores were significantly higher for triadic pyramids than for triadic trees in both age groups (respectively  $W_+ = 59$ ,  $p_{corr} = .019$ ,  $r = .70$ , 95% CI = [.30, .89] for younger participants, and  $W_+ = 45$ ,  $p_{corr} = .008$ ,  $r = .89$ , 95% CI = [.89, .90] for older

participants, Holm-Bonferroni corrected p-values). The average triadic pyramidal metric was significantly higher than predicted by chance in both age groups (respectively  $M_{younger} = .35$ ,  $W_+ = 61$ ,  $p_{corr} = .010$ ,  $r = .75$ , 95% CI = [.40, .89], for younger participants, and  $M_{older} = .50$ ,  $W_+ = 45$ ,  $p_{corr} = .008$ ,  $r = .89$ , 95% CI = [.89, .90] for older participants, Holm-Bonferroni corrected p-values). Thus, triadic pyramids were over-represented in dominance networks in both age groups. In contrast, average normalized Z-scores for triadic trees did not differ significantly from chance in any of the age groups (respectively  $M_{younger} = -.08$ ,  $W_+ = 21$ ,  $p_{corr} = .320$ ,  $r = .32$ , 95% CI = [.03, .89] for younger participants, and  $M_{older} = -.14$ ,  $W_+ = 6$ ,  $p_{corr} = .109$ ,  $r = .65$ , 95% CI = [.14, .90] for older participants, Holm-Bonferroni corrected p-values).

In short, age had no detectable effects on the triadic pyramidal motif observed in children's group. Furthermore, separate analyses conducted on data from younger and older participants confirmed the results observed for the full sample.

## Supplementary Methods and Results

### Additional information about studies with adults (Studies S1<sub>ab</sub>, 2-4)

**Participants.** 160 adults participated in studies testing human adults' inferences (Study S1<sub>a</sub>:  $n = 20$ ; mean age = 22.1 y; range = 19–28 y, 11 females; Study S1<sub>b</sub>:  $n = 20$ ; mean age = 23 y; range = 19–30 y, 11 females; Study 2:  $n = 40$ ; mean age = 23.05 y; range = 19–34 y, 21 females; Study 3, pyramidal condition:  $n = 20$ ; mean age = 22.9 y; range = 19–29 y, 12 females; Study 3, tree condition:  $n = 20$ ; mean age = 22.35 y; range = 19–29 y, 10 females; Study 4 pyramidal condition:  $n = 20$ ; mean age = 22.8 y; range = 19–32 y, 11 females; Study 4 tree condition:  $n = 20$ ; mean age = 23.15 y; range = 19–33 y, 11 females). One participant was tested but excluded from analysis for cheating (i.e., drawing the relations on a sheet of paper). Each participant was enrolled in only one of the Studies.

Although no study tested the pyramidal inference that we investigated, past studies testing adults participants' sensitivity to the structural regularities of dominance structures typically show large effect sizes<sup>1,2</sup>. An a priori power analysis performed with G\*power<sup>3</sup> (v.3.1), assuming a large effect size (.8), revealed that a sample of 15 participants per condition was needed to achieve a power of .8 when comparing participants' inference score to the level of performance predicted by chance with two-tailed one-sample t-tests ( $\alpha = .05$ ). Given that adults are relatively easy to recruit, we set our sample size to 20 per condition with a between-subject treatment in each Study. The participants were recruited by sending announcements on several cognitive science mailing list distributed in the Lyon area, and by advertising the study on social media. All participants gave their informed written consent prior to their inclusion in the studies.

Instructions. Prior to the experiment, the participants received instructions indicating that they would be learning social relationships between individuals. The instructions read as follows:

*“You will have to answer questions about relationships between 8 individuals: either [symmetric relation used in the study: “friendship” or “enmity”] relationships, or dominance (power) relationships. For each question, two first names will be displayed on the screen. You will answer the question with one of the two names by pressing the left arrow key to select the name on the left, or by pressing the right arrow key to select the name on the right. Your goal is to give as many correct answers as possible.*

*In the first phase of the experiment, once you will have answered a question, the word “True” or “False” will appear on the screen, along with a sentence stating the correct answer. It is normal that you do not know the answers to the questions at the very beginning of the experiment. In the second phase of the experiment, you will no longer receive information on the correct answers.*

*You can take a break between each series of questions. After the break, a new round begins with the same questions displayed in a different order. You will now see two examples of questions: an example of a [symmetric relation used in the study: “friendship” or “enmity”] relation, and an example of a dominance (power) relationship.*

*Press any key to continue”*

**Warm-up phase.** Next, the participants were enrolled in two warm-up trials whose purpose was to familiarize them with the experiment. In each warm-up trial, the participants were asked mock questions about the relations between individuals represented by letters. The participants saw a question appear on top of the screen (“Who is X’s friend/enemy?” for the

first warm-up trial, and “*Who dominates?*” for the second warm-up trial). After 1.5s post-trial onset, two letters (Y and Z for the first warm-up trial, A and B for the second warm-up trial) appeared below the question, one on each side of the screen. The participants had to select one of these two letters within 5s by pressing the keyboard’s right or left arrow (to select the letter on the matching side). Right after the participants’ response or after 5s elapsed, feedback appeared on the screen for 5.5s, after which the trial ended. The feedback indicated whether participants’ response was “True” or “False”, and stated the correct answer (“*A dominates B*” for dominance relationships, “*Y is X’s friend*” for friendships, and “*Y is X’s enemy*” for enmity relations). Thus, the two warm-up trials followed the exact same procedure as the trials of the subsequent learning phase with the following exceptions: (i) the agents were represented by letters (rather than full names), and (ii) the relations used during the warm-up trials were not used during the subsequent learning and test phases.

After the warm-up phase, the participants were enrolled in the learning and test phase that proceeded as described in the main text. In-between the learning and test phase, the following message appeared: “*You finished the first part. From now on, correct answers to questions will no longer be shown. Press on any key to continue*”.

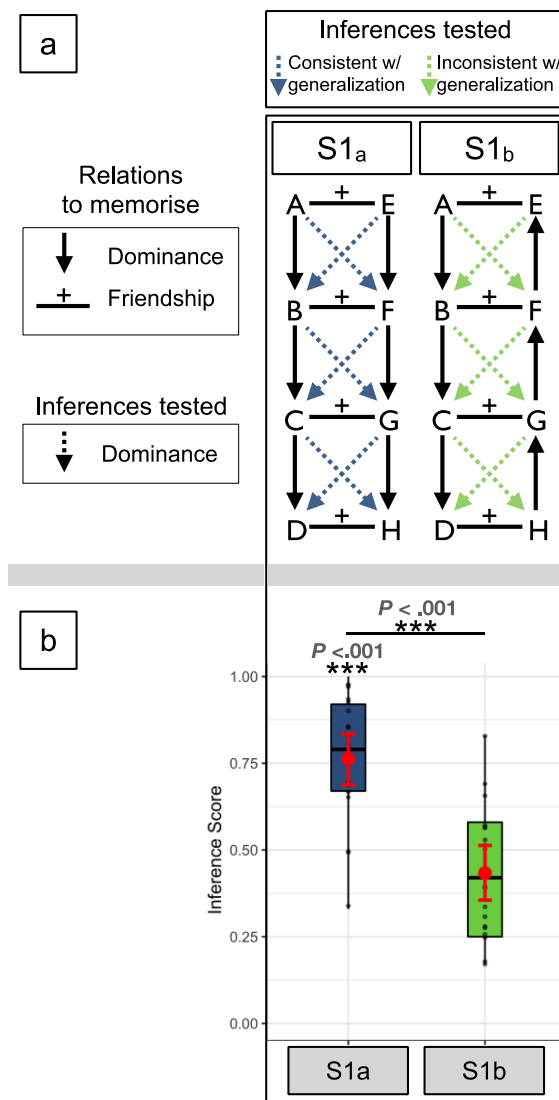
**Counterbalanced factors.** For each participant, a different name was randomly assigned to each position in the social network. Names were chosen from one of two lists of eight names of a given gender, either female (Marie-Julia-Carole-Nathalie-Delphine-Françoise-Hélène-Audrey) or male (Maxime-Denis-Bernard-Stéphane-Jean-Olivier-Félix-Arthur). Whether we used the list with female or male names was counterbalanced across participants. In Study 2, we counterbalanced across participants whether we used the sentences “*Who dominates?*” and “[*name 1*] dominates [*name 2*]” or the sentences “*Who is subordinate?*” “[*name 1*] is subordinate to [*name 2*]” to convey information about dominance

relations. Since we observed no effect of phrasing in Study 2, in Studies 3-4, we used only the sentences “*Who dominates?*” and “[*name 1*] dominates [*name 2*]” to convey information about dominance relations. In all studies, we used the sentences “*Who is [name 1]’s friend/enemy?*” and “[*name 2*] is [*name 1*]’s friend/enemy” to convey information about symmetrical relations. The order of the trials was randomized within each block of the learning and test phases. The side of the correct answer (right or left side of the screen) was counterbalanced across trials.

**Studies S1<sub>a-b</sub>.** Studies S1<sub>a-b</sub> ensured that participants drew systematic inferences about novel dominance relations in our design. In Study S1<sub>a</sub>, the network that the participants had to memorize included four friendship dyads linked by two chains of dominance relations that ran in the same direction (Fig. S1a). In Study S1<sub>a</sub>, if participants generalize dominance relations across friendships, they are expected to infer that if A dominates B and B is friend with F, then A is likely to dominate F. Study S1<sub>b</sub> was identical to Study S1<sub>a</sub>, except that the direction of one chain of dominance relations was reversed (Fig. S1a) so that inferences based on generalizing dominance across friendships would cancel each other out. For example, the participants learned that A dominated B and that B was friend with F, a pattern that could be used to infer that A dominated F. Yet, they also learned that F dominated E, and that E was friend with A, a pattern that could be used to infer that F dominated A.

A full-factorial ANOVA run on inference scores with Study (S1<sub>a</sub> vs. S1<sub>b</sub>) and names’ gender (female vs. male) as between-subject factors revealed only a main effect of Study, indicating that inference scores were significantly higher in Study S1<sub>a</sub> than in Study S1<sub>b</sub> ( $F(1, 36) = 31.29, p < .001, \eta^2_p = .46, 95\% \text{ CI} = [.26, 1]$ ). Follow-up tests confirmed that inference scores were significantly higher than predicted by chance in Study S1<sub>a</sub>, and not in Study S1<sub>b</sub> (see Table S4). Thus, participants generalized dominance relations across friendships in our

design. Moreover, this effect disappeared when inferences based on generalizing dominance across friendships cancelled each other out. In subsequent studies, we investigated whether adults' inferences about unobserved dominance relations were consistent with the triadic pyramidal motif of dominance networks.



*Figure S1. Network structures and results of Studies S1<sub>ab</sub>. a. Schematic representation of the social networks used in Studies S1<sub>ab</sub> (n = 20/study). Each arrow represents a dominance relation (pointing towards the subordinate agent). Line segments represent friendships (“+” on top). Solid lines represent relations that the participants had to memorize during the learning phase. Dotted lines represent the novel relations that the participants had to infer*

during the test phase, with the direction of the arrow representing what we treated as a correct answer when computing inference scores. In Studies  $SI_{ab}$  the relations that the participants had to infer could be consistent with generalizing social dominance across friendships ( $SI_a$ , in blue), or inconsistent with generalizing social dominance across friendships ( $SI_b$ , in green). Note that the participants never saw these graphical representations of social networks; they received information about relations one by one in a written format. b. Inference scores in Studies  $SI_{ab}$ . Black dots and error bars indicate means and SE. Horizontal bars within boxes indicate medians, and boxes indicate the middle 2 quartiles of data. Upper whiskers indicate data up to 1.5 times the interquartile range above the third quartile, and lower whiskers indicate data up to 1.5 times the interquartile range below the first quartile. Grey dots represent individual data points. The effect of Studies ( $SI_a$  vs.  $SI_b$ ) on inference scores was assessed with a two-tailed full-factorial ANOVA run on inference scores with Study ( $SI_a$  vs.  $SI_b$ ) and names' gender (female vs. male) as between-subject factors. For comparisons of inferences scores against chance in each Study,  $p$  values were assessed with two-tailed one-sample  $t$ -tests and were corrected for multiple comparisons across Studies ( $SI_{ab}$ ) using the Holm-Bonferroni procedure. \*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ .

**Additional results for Study 2.** The ANOVA ran on Study 2's data revealed a main effect of Condition, indicating that in Study 2, inference scores were significantly higher for inferences consistent with a triadic pyramid rather than with a triadic tree ( $F(1, 36) = 4.45, p = .042, \eta^2_p = .11, 95\% \text{ CI} = [0, 1]$ ). For Study 2, the ANOVA also revealed a main effect of name's gender ( $F(1, 36) = 6.19, p = .018, \eta^2_p = .15, 95\% \text{ CI} = [.02, 1]$ ), and an interaction between condition and name's gender ( $F(1, 36) = 6.80, p = .013, \eta^2_p = .16, 95\% \text{ CI} = [.02, 1]$ ), indicating that the effect of Condition (pyramid vs. tree) was more pronounced when the names used to represent individuals in the network were female rather than male. Note

however, that the robustness of the effect of name's gender observed in Study 2 is questionable, since we did not observe it again in Studies 3-4.

#### Additional information about studies with infants (Studies 5<sub>ab</sub>-6<sub>ab</sub>-7<sub>ab</sub>)

**Participants.** An a priori power analysis performed with G\*power<sup>3</sup> (v.3.1), assuming an effect size of .667<sup>4</sup>, revealed that a sample of 20 participants per group was needed to achieve a power of .8 when evaluating the effect of test coherence on looking times by two-tailed paired t-tests ( $\alpha = .05$ ). Thus, we included 20 infants per Study (Study 5<sub>a</sub>:  $M_{age} = 433$  d; range = 389–463 d, 9 females; Study 5<sub>b</sub>:  $M_{age} = 426$  d; range = 391–456 d, 10 females; Study 6<sub>a</sub>:  $M_{age} = 433$  d; range = 400–466 d, 10 females; Study 6<sub>b</sub>:  $M_{age} = 429$  d; range = 399–460 d, 9 females; Study 7<sub>a</sub>:  $M_{age} = 430$  d; range = 400–460 d, 9 females; Study 7<sub>b</sub>:  $M_{age} = 433$  d; range = 400–468 d, 11 females). Each participant was enrolled in only one of the Studies.

Additional infants participated but were excluded from analyses because of crying or leaving their parent's lap before the end of the experiment (11), parental interference (4), impossibility to code the infants' gaze — head off-camera (3), experimental error (14), inattentiveness — i.e., looking at the familiarization movies or at the competitive interaction shown during test movies for less than 75% of their duration (10) —see details below— and technical failure (1). The infant participants were recruited by sending letters to a randomly selected sample of children born in two large French cities (Lyon and Paris). The parents of all participants gave their informed written consent prior to their inclusion in the studies.

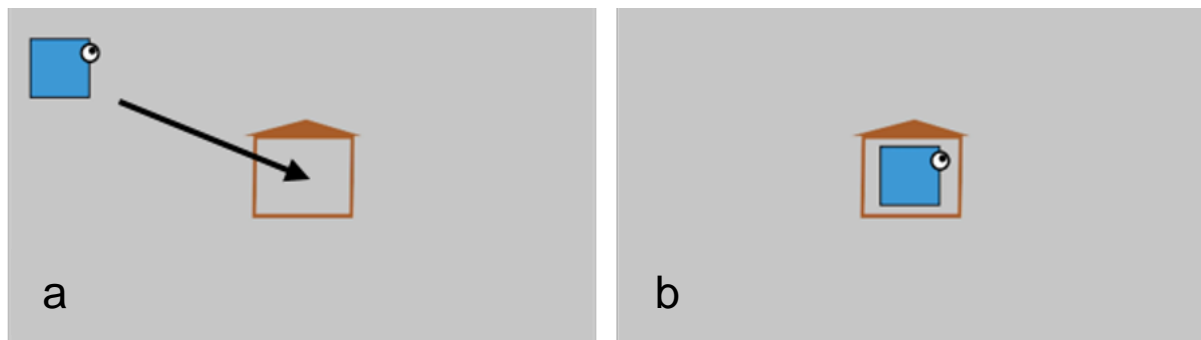
#### **Materials and Procedure.**

**Stimuli and apparatus.** Infants were tested in a dimly lit soundproof room, seating on their caregiver's lap approximately 70 cm from a 24-inch LCD monitor on which the stimuli were presented. A hidden camera (temporal resolution: 50 frames/s) recorded infants' looking behavior. Caregivers were instructed to close their eyes during the entire procedure. During

the experiment, infants watched 2D animations involving four geometrical figures with eyes (representing agents): a blue square, a green circle, a red triangle and a yellow star. At the center of the screen, a marked area which looked like a house was delimited by brown lines and a triangle (see Figures S2-S5). The marked area was too small to host more than one agent. In all animations, sounds were played during the actions of the agents to attract and maintain the infants' attention to the screen. The participants were enrolled in experimental studies (5<sub>a</sub>, 6<sub>a</sub>, 7<sub>a</sub>), or in control studies (5<sub>b</sub>, 6<sub>b</sub>, 7<sub>b</sub>).

### Studies 5<sub>a</sub>, 6<sub>a</sub>, 7<sub>a</sub>

*Warm-up phase.* Infants saw first four "warm-up videos" (7s each) where each agent was alone and was moving from one of the corners of the screen towards the marked area (Fig. S2a); next the agent stayed in the marked area motionless for 2s (Fig. S2b). These sequences aimed at conveying that the individual goal of each agent was to occupy the marked area.



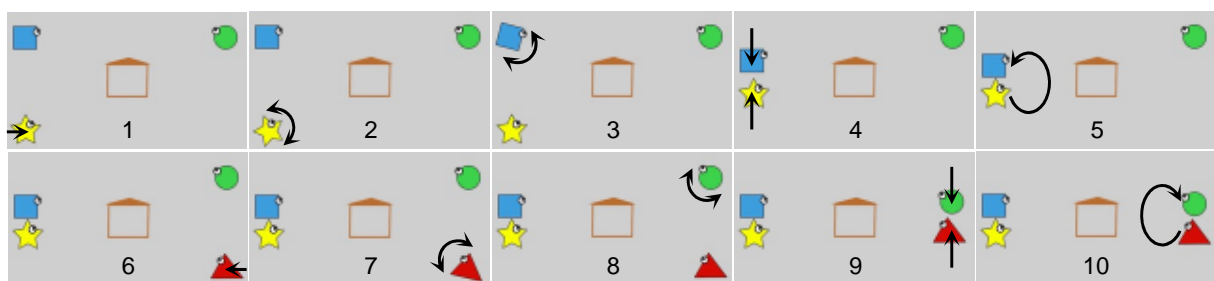
*Figure S2. Stills from the warm-up videos. The arrow represents the agent's movement (it was not visible in the videos shown to the participants). a. Agent's initial position. b Agent's final position.*

*Familiarization phase.* Next, infants saw four "familiarization videos" providing the participants with information about the relations between the four agents present on screen

(named here A, B, C and D). These videos were designed to convey that (i) agents A and B were allies, (ii) agents C and D were allies, and that (iii) A dominated C.

To alleviate participants' boredom, we used two types of familiarization videos: long (22s) and short ones (13s). In the long familiarization videos, two agents were present on the screen initially (one at each top corner of the screen). The third and fourth agents successively entered the scene and positioned themselves at the bottom of the screen, right below their respective allies. Next, the movies provided evidence for the two alliance relationships (between A and B, and C and D respectively), using cues adapted from previous studies<sup>5-7</sup>. For each pair of allies, agents first responded to each other by taking turns at oscillating while a sound was played. Next, the agents approached each other, before moving together in a synchronized fashion along the same circular path. At the end of their circular movement, the agents stayed in close spatial proximity (see Figure S3).

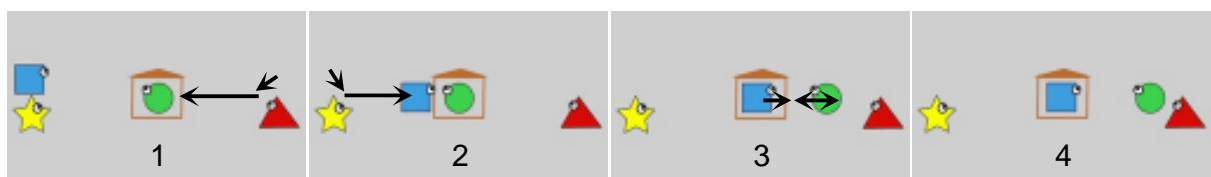
The short versions of the familiarization videos were identical to long ones, except that agents did not move together in a synchronized fashion along the same circular path to demonstrate their alliance relationships. They simply oscillated in a turn-taking fashion, before moving next to each other (see Figure S3). Each participant saw two long and two short familiarization videos, in the following order : long-short-short-long.



*Figure S3. Alliance events of familiarization videos in experimental studies (5<sub>a</sub>, 6<sub>a</sub>, 7<sub>a</sub>). Two agents were present on screen at the beginning of the sequence of events; next, a third agent*

*entered the screen (panel 1). The third agent and its ally reacted contingently to one another by oscillating back and forth alternatively (panels 2,3). Next, the two allies approached each other (panel 4) and performed synchronized movements together along a circular path (panel 5). Subsequently, a fourth agent entered the screen (panel 6). The fourth agent and its ally performed the same affiliative actions as the first pair of allies (panels 7-10). The long familiarization videos, included the complete sequence of alliance events (panels 1-10); the short familiarization videos included only the events shown on panels 1-4, 6-9).*

In each of the familiarization videos, the sequence providing information about alliance relations was followed by events that served to establish a dominance relationship between two individuals (one from each pair of allies). To convey information about dominance relations, we used cues adapted from previous studies<sup>8,9</sup>. One of the agents initially located at the top of the screen (here called “subordinate”) approached the marked area, and entered it. Subsequently, the second agent located initially at the top of the screen (here called “dominant”), also approached the marked area and pushed the subordinate agent out of it. Next, the subordinate and the dominant agent attempted to push each other away from the marked area three times. For each attempt, the dominant agent succeeded, and the subordinate agent failed. The dominant agent succeeded in pushing out the subordinate agent and occupying the marked area thrice in each familiarization video. At the end of this sequence, the dominant agent remained inside the marked area, while the subordinate agent stayed outside (see Figure S4).



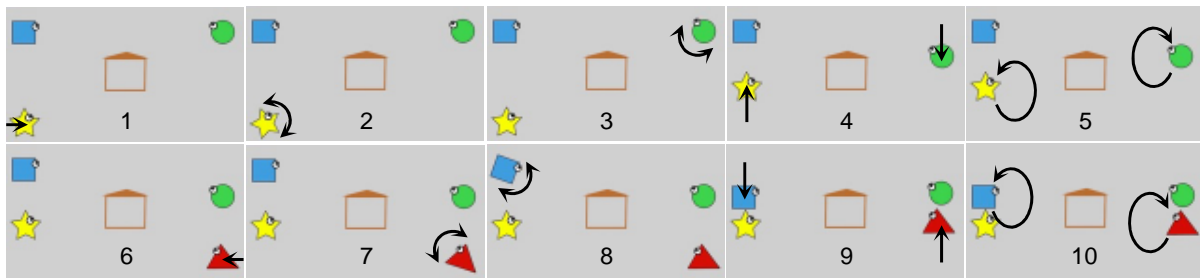
*Figure S4. Pictures of the dominance events of the familiarization videos. The subordinate agent entered the marked area (panel 1) but was pushed out by the dominant agent three times (panels 2, 3). At the end of the dominance events, the dominant agent stayed inside and the subordinate agent stayed outside the marked area (panel 4).*

*Test phase.* The test movies were identical to the short familiarization videos, except for the identity of the two characters competing to occupy the marked area. In Study 5<sub>a</sub>, the ally of the dominant agent competed with the ally of the subordinate agent. In Study 6<sub>a</sub>, the dominant agent competed with the ally of the subordinate agent. In Study 7<sub>a</sub>, the subordinate agent competed with the ally of the dominant agent. In the coherent test movies, the dominant agent or its ally prevailed. In the incoherent test movies, the subordinate agent or its ally prevailed. Once the competitive interaction between the agents was over, the screen froze and we measured looking times, up to the point the infants looked away for >2 s, or after 45 s elapsed since the beginning of the measurement. Each participant saw a coherent and an incoherent test movie (order of presentation counterbalanced across participants).

We also counterbalanced across participants: the shape of the agent which was dominant, subordinate, allied with the dominant, or allied with the subordinate in the relationship movies; the side of the screen occupied by the dominant agent and its ally (left or right) — the side of the screen occupied by the subordinate agent and its ally varied accordingly. To facilitate infants' identification of agents, their initial position was kept constant for each individual participant. As a result of our counterbalanced factors, we ensured that each specific test movie was used equally often as a coherent test movie, and as an incoherent test movie.

**Studies 5<sub>b</sub>, 6<sub>b</sub>, 7<sub>b</sub>**

Studies 5<sub>b</sub>, 6<sub>b</sub>, and 7<sub>b</sub> were identical to Studies 5<sub>a</sub>, 6<sub>a</sub>, and 7<sub>a</sub>, except that we made information about alliances ambiguous by modifying the order of the agents' movements (see Figure S5). In the familiarization and test videos of Studies 5<sub>b</sub>, 6<sub>b</sub>, and 7<sub>b</sub>, each agent (i) reacted contingently to the agent located at the opposite corner of the screen by oscillating and emitting sounds in a turn-taking fashion. Next, the agents located at opposite corners of the screen (ii) moved together along opposite circular path. Moreover, each agent also (iii) approached, and (iv) stayed next to the agent located on its own screen side. The competitive interactions conveying information about dominance were the same in Studies 5<sub>b</sub>, 6<sub>b</sub>, and 7<sub>b</sub> as in Studies 5<sub>a</sub>, 6<sub>a</sub>, and 7<sub>a</sub>. In Studies 5<sub>b</sub>, 6<sub>b</sub>, and 7<sub>b</sub>, the test movies in which the dominant agent or the agent located on the dominant agent's screen side prevailed are called coherent; the test movies in which the other agent prevailed are called incoherent. The movies of Studies 5<sub>b</sub>, 6<sub>b</sub>, and 7<sub>b</sub> were generated by reordering the temporal order of the events in the movies of Studies 5<sub>a</sub>, 6<sub>a</sub>, and 7<sub>a</sub> respectively.



*Figure S5. Alliance events of familiarization videos in control studies (5<sub>b</sub>, 6<sub>b</sub>, 7<sub>b</sub>). Agents located at opposite corners of the screen oscillated in a turn-taking fashion and moved together along a circular path (2 to 5; 7 to 10). Yet, each of them stayed near the other agent located their side of the screen (10).*

### **Coding**

We coded frame-by-frame whether infants looked at the screen or looked away thanks to the software Anvil 5<sup>10</sup>. Blinks were considered as looks away if they lasted more than 0.2 seconds. Infants looking for less than 75% of the duration of familiarization movies and for less than 75% of the duration of the scene in which agents competed by pushing each other during test movies were considered “inattentive” and were excluded from analysis. These criteria were set before collecting data. Looking times at test outcomes were measured from the moment the agents stopped moving, up to the moment the infant looked away for 2 consecutive seconds, or after 45 seconds elapsed. For each study, one of the co-authors (H. Pantecouteau for studies 5<sub>ab</sub>, N. Goupil for studies 6<sub>ab</sub>-7<sub>ab</sub>) served as primary coder and coded all the data. A second coder who was unaware of the hypotheses of the study double-coded 40% of randomly selected data. The correlations between the coders’ measures of looking times were high (Spearman’s  $\rho = 0.98$ ). Subsequently, statistical analyzes were performed on the data from the primary coders.

## Supplementary Tables

Group	<i>n</i>	<i>W+</i>	<i>p<sub>corr</sub></i>	<i>r</i> [95% CI]
Human Children (Primates)	20	203	<b>0.001088</b>	<b>.82</b> [.68, .88]
Non-human primates (Primates)	81	2356.5	2.632e-05	.52[.34, .67]
Ungulates (Artiodactyla)	38	632	<b>0.0001422</b>	<b>.69</b> [.47, .85]
Carnivores (Carnivora)	30	417.5	<b>0.000735</b>	<b>.69</b> [.48, .84]
Rodents (Rodentia)	53	1346.5	1.744e-08	.83[.74, .87]
Birds (Passeriformes)	29	357	<b>0.001212</b>	<b>.67</b> [.36, .88]
Social insects (Hymenoptera)	17	124	<b>0.0249</b>	<b>.55</b> [.09, .88]
Other	50	806.5	<b>0.0208</b>	<b>.37</b> [.10, .60]

*Table S1. Detailed statistics comparing the average triadic pyramidal metric against chance-level (.5) for each taxonomic group in Study 1<sub>a</sub>. P values were assessed with two-tailed one sample Wilcoxon tests and were corrected for multiple comparisons across taxonomic categories using the Holm-Bonferroni procedure. The effect size *r* is the Z statistic divided by the square root of the sample size ( $Z/\sqrt{n}$ ). Significant results in bold.*

Group	<i>n</i>	<i>W+</i>	<i>p<sub>corr</sub></i>	<i>r</i> [95% CI]
Human Children (Primates)	20	200	0.0003865	.79 [.59, .88]
Non-human primates (Primates)	81	2620	3.792e-05	.50 [.32, .66]
Ungulates (Artiodactyla)	38	672	1.316e-05	.71 [.52, .84]
Carnivores (Carnivora)	30	394	0.001515	.61 [.32, .81]
Rodents (Rodentia)	53	1390	1.936e-08	.82 [.71, .87]
Birds (Passeriformes)	29	388	0.0003865	.68 [.45, .85]
Social insects (Hymenoptera)	17	131	0.0079	.63 [.25, .88]
Other	50	946	0.0059	.42 [.17, .64]

*Table S2. Detailed statistics assessing the effect of pattern (triadic pyramid vs. triadic tree) on the average normalized z-score. P values were assessed with two-tailed Wilcoxon tests for matched pairs, and were corrected for multiple comparisons across taxonomic categories using the Holm-Bonferroni procedure. The effect size r is the Z statistic divided by the square root of the sample size ( $Z/\sqrt{n}$ ). Significant results in bold.*

Group	pattern	<i>n</i>	<i>W+</i>	<i>p<sub>corr</sub></i>	<i>r</i> [95% CI]
Human Children (Primates)	Pyramid	20	205	2.1420e-04	.83 [.70, .88]
Non-human primates (Primates)	Pyramid	81	3013	6.8250e-09	.71 [.59, .79]
Ungulates (Artiodactyla)	Pyramid	38	669	4.3180e-05	.70 [.50, .83]
Carnivores (Carnivora)	Pyramid	30	453	3.1200e-06	.83 [.73, .87]
Rodents (Rodentia)	Pyramid	53	1405	3.2860e-08	.84 [.78, .87]
Birds (Passeriformes)	Pyramid	29	411	4.5440e-05	.78 [.60, .87]
Social insects (Hymenoptera)	Pyramid	17	136	2.2120e-02	.68 [.36, .88]
Other	Pyramid	50	1108	8.5500e-05	.64 [.46, .78]
Human Children (Primates)	Tree	20	43	1.1520e-01	.52 [.12, .85]
Non-human primates (Primates)	Tree	81	1499	1.0000e+00	.08 [.004, .3]
<b>Ungulates (Artiodactyla)</b>	<b>Tree</b>	<b>38</b>	<b>134</b>	<b>2.9120e-03</b>	<b>.55 [.28, .80]</b>
Carnivores (Carnivora)	Tree	30	198	1.0000e+00	.13 [.01, .48]
<b>Rodents (Rodentia)</b>	<b>Tree</b>	<b>53</b>	<b>104</b>	<b>1.5850e-06</b>	<b>.74 [.56, .87]</b>
Birds (Passeriformes)	Tree	29	117	1.4550e-01	.40 [.07, .72]
Social insects (Hymenoptera)	Tree	17	38	2.8560e-01	.44 [.04, .88]
Other	Tree	50	697	1.0000e+00	.08 [.003, .35]

*Table S3. Detailed statistics comparing the average normalized z-scores against chance-level (0) for each taxonomic group in Study 1<sub>a</sub>. P values were assessed using two-tailed one sample Wilcoxon tests and were corrected for multiple comparisons across taxonomic categories using the Holm-Bonferroni procedure. The effect size *r* is the Z statistic divided by the square root of the sample size ( $Z/\sqrt{n}$ ). Significant results in bold.*

Study (Condition)	Inference score		One sample t-test		
	<i>M</i>	<i>SD</i>	<i>t</i>	<i>p<sub>corr</sub></i>	<i>d</i> [95%CI]
<b>Study S1a</b>	.76	.18	<b>6.45</b>	<b>&lt;.001</b>	<b>1.44</b> [.89, 2.58]
Study S1b	.43	.18	-1.62	.122	-.36 [-.93, .08]
<b>Study 2 (Pyramid)</b>	.64	.27	<b>3.24</b>	<b>.005</b>	<b>.51</b> [.19, .96]
Study 2 (Tree)	.53	.25	0.68	.498	.11 [-.20, .42]
<b>Study 3 (Pyramid)</b>	.62	.18	<b>2.95</b>	<b>.016</b>	<b>.66</b> [.27, 1.11]
<b>Study 3 (Tree)</b>	.41	.17	<b>-2.31</b>	<b>.032</b>	<b>-.52</b> [-1.43, -.03]
<b>Study 4 (Pyramid)</b>	.66	.21	<b>3.43</b>	<b>.006</b>	<b>.77</b> [.42, 1.25]
Study 4 (Tree)	.44	.14	-1.80	.088	-.40 [-.97, .04]

*Table S4. Means and standard deviations of inference scores and their statistical comparisons to the level of performance predicted by chance (0.5) across Studies with adults (S1<sub>ab</sub>; S2-4) and conditions. All statistical tests were two-tailed. Effect sizes (Cohen's *d*) are the sample mean minus the mean predicted by chance (.5) divided by the estimated standard deviation. Significant results in bold. For each Study, *p*-value were corrected for multiple comparisons across conditions using the Holm-Bonferroni procedure.*

Study	Coherent test		Incoherent test		Paired t-test (log-transformed data)			Wilcoxon signed-rank test (raw data)		
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>t</i> (19)	<i>p</i> <sub>corr</sub>	<i>d</i> [95%CI]	<i>W</i> <sup>+</sup>	<i>p</i> <sub>corr</sub>	<i>r</i> <sub>rb</sub> [95%CI]
<b>Study 5a</b>	<b>13.41</b>	<b>14.52</b>	<b>23.08</b>	<b>14.71</b>	<b>-3.11</b>	<b>.012</b>	<b>-0.74 [-1.11, -.36]</b>	<b>31</b>	<b>.012</b>	<b>-.61 [-.88, -.28]</b>
Study 5b	20.48	15.11	21.98	17.50	.18	1.00	.04 [-.47, .45]	97	1.00	-.06 [-.48, .38]
<b>Study 6a</b>	<b>21.34</b>	<b>12.95</b>	<b>28.54</b>	<b>13.90</b>	<b>-3.29</b>	<b>.008</b>	<b>-0.74 [-1.38, -.32]</b>	<b>28</b>	<b>.009</b>	<b>-.64 [-.87, -.28]</b>
Study 6b	22.76	14.54	19.28	13.40	.99	.668	.22 [-.22, .67]	121	.255	.35 [-.09, .72]
Study 7a	23.04	16.53	22.89	14.14	.127	1.00	.028 [-.49, .46]	116	1.00	.09 [-.34, .55]
Study 7b	21.58	16.43	22.24	17.95	-.11	1.00	-.02 [-.43, .46]	106	1.00	.01 [-.43, .46]

*Table S5. Means and standard deviations of looking times at test events across Studies with infants (Studies 5<sub>ab</sub>, 6<sub>ab</sub>, 7<sub>ab</sub>). The effect of test coherence (coherent vs. incoherent) was assessed with t-tests for matched pairs (on log-transformed data), and Wilcoxon signed-rank tests for matched pairs (on raw data). All statistical tests were two-tailed. Cohen's *d* is the mean difference of the paired sample values divided by the standard deviation of the difference. The effect size *r* is the Z statistic divided by the square root of the sample size ( $Z/\sqrt{n}$ ). Significant results in bold. *P* values were corrected for multiple comparisons using the Holm-Bonferroni procedure applied for each Study pair (5<sub>ab</sub>, 6<sub>ab</sub>, 7<sub>ab</sub>).*

Full_citation	Source	File_name	Number of individuals
Strayer, F. F., & Trudel, M. (1984). Developmental changes in the nature and function of social dominance among young children. <i>Ethology and Sociobiology</i> , 5(4), 279-295.	Appendix A. 1	Strayer_Trudel_1	9
Strayer, F. F., & Trudel, M. (1984). Developmental changes in the nature and function of social dominance among young children. <i>Ethology and Sociobiology</i> , 5(4), 279-295.	Appendix A. 2	Strayer_Trudel_2	11
Strayer, F. F., & Trudel, M. (1984). Developmental changes in the nature and function of social dominance among young children. <i>Ethology and Sociobiology</i> , 5(4), 279-295.	Appendix A. 3	Strayer_Trudel_3	14
Strayer, F. F., & Trudel, M. (1984). Developmental changes in the nature and function of social dominance among young children. <i>Ethology and Sociobiology</i> , 5(4), 279-295.	Appendix A. 4	Strayer_Trudel_4	18
Strayer, F. F., & Trudel, M. (1984). Developmental changes in the nature and function of social dominance among young children. <i>Ethology and Sociobiology</i> , 5(4), 279-295.	Appendix A. 5	Strayer_Trudel_5	16
Russon, A. E., & Waite, B. E. (1991). Patterns of dominance and imitation in an infant peer group. <i>Ethology and sociobiology</i> , 12(1), 55-73.	Table 2	Russon_Waite_1	12
Strayer, F. F., & Strayer, J. (1976). An ethological analysis of social agonism and dominance relations among preschool children. <i>Child Development</i> , 47, 980-989.	Figure 1	Strayer_Strayer_1	17
Strayer, J., & Strayer, F. F. (1978). Social aggression and power relations among preschool children. <i>Aggressive Behavior</i> , 4(2), 173-18	Table IV	Strayer_Strayer_2	19
Sluckin, A. M., & Smith, P. K. (1977). Two approaches to the concept of dominance in preschool children. <i>Child Development</i> , 48, 917-923.	Table 1	Sluckin_Smith_1	12
Sluckin, A. M., & Smith, P. K. (1977). Two approaches to the concept of dominance in preschool children. <i>Child Development</i> , 48, 917-923.	Table 2	Sluckin_Smith_2	11
Strayer, F. (1978). L'organisation sociale chez l'enfant d'âge préscolaire. <i>Sociologie et sociétés</i> , 10(1), 43-64.	Figure 5	Strayer_1	11
Strayer, F. F., & Noel, J. M. (1986). The prosocial and antisocial functions of preschool aggression: An ethological study of triadic conflict among young children. <i>Altruism and aggression: Biological and social origins</i> , 107-31.	Figure 4.3	Strayer_Noel_1	15
Strayer, F. F., & Noel, J. M. (1986). The prosocial and antisocial functions of preschool aggression: An ethological study of triadic conflict among young children. <i>Altruism and aggression: Biological and social origins</i> , 107-31.	Figure 4.3	Strayer_Noel_2	17
Missakian, E., & Hamer, K. (1974). <i>Aggression and Dominance Relations in Young Children</i> . Synanon foundation. Reproduced by the US department of Health, Education & Welfare	Matrix 1	Missakian_Hamer_1	13
Missakian, E., & Hamer, K. (1974). <i>Aggression and Dominance Relations in Young Children</i> . Synanon foundation. Reproduced by the US department of Health, Education & Welfare	Matrix 2	Missakian_Hamer_2	13
Vaughn, B. E., & Waters, E. (1981). Attention structure, sociometric status, and dominance: interrelations, behavioral correlates, and relationships to	Table 1	Vaughn_Waters_1	20

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Gauthier, R., & Jacques, M. (1985). La dominance et l'affiliation chez les enfants d'âge pré-scolaire: analyse transversale. <i>Ethologie et Développement de l'Enfant</i> . Stock/Laurence Pernoud, Paris, 309-328.	Figure 15.2	Jacques_Gauthier_1	9
Gauthier, R., & Jacques, M. (1985). La dominance et l'affiliation chez les enfants d'âge pré-scolaire: analyse transversale. <i>Ethologie et Développement de l'Enfant</i> . Stock/Laurence Pernoud, Paris, 309-328.	Figure 15.2	Jacques_Gauthier_2	19

Table S6. Metadata for human data (Studies 1<sub>ab</sub>).

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