nature human behaviour

Article

https://doi.org/10.1038/s41562-023-01634-5

Human and animal dominance hierarchies show a pyramidal structure guiding adult and infant social inferences

Received: 22 December 2022

Accepted: 17 May 2023

Olivier Mascaro[1], **Nicolas Goupil**[2], **Hugo Pantecouteau**[3], **Adeline Depierreux**[1], **Jean-Baptiste Van der Henst**[4] & **Nicolas Claidière**[5]

This study 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 non-human 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. By contrast, human participants do not draw equivalent inferences based on a tree-shaped pattern with a similar complexity to 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.

The distribution of social power and wealth in societies is often represented by pyramids[1,2]. In many institutions (for example, firms or states), the distribution of formal ranks, statuses and rewards is pyramidal, with fewer individuals at the top than at the bottom[3,4], sometimes in cases in which non-pyramidal organizations might yield better team performance[5]. 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.

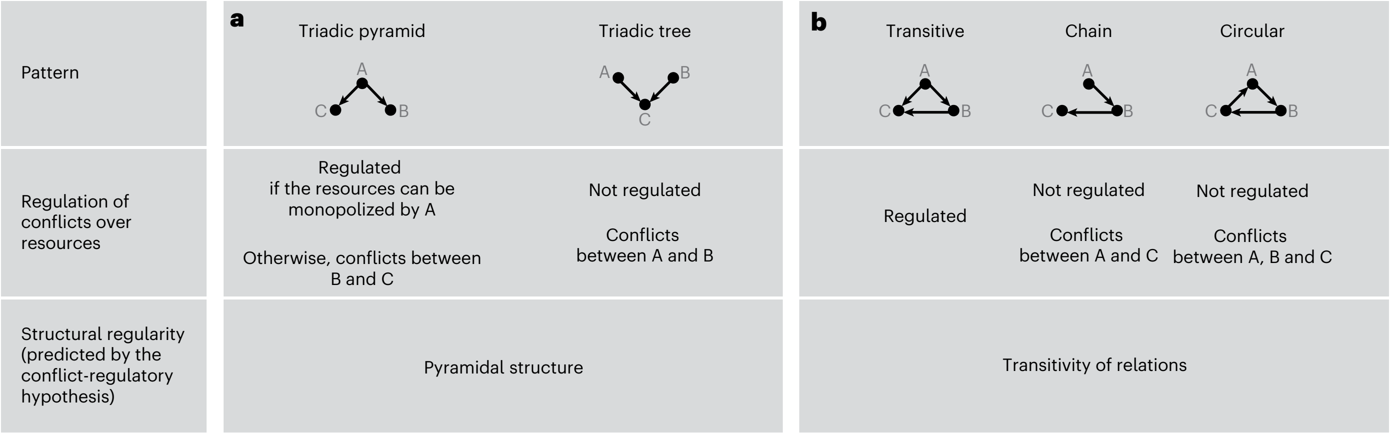
We define dominance as a social relation in which dominant individuals tend to prevail when their goals conflict with those of their subordinates[6,7]. Social dominance relations are observed in a wide range of human and animal societies[8,9]. Dominant individuals predominantly control access to resources,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

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[16,17]. Stable dominance relations, in which subordinates yield to dominant individuals, are hypothesized to function as a means of regulating resource access while avoiding costly conflicts[10–12,18,19].

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

---

[1]Université Paris Cité, CNRS, Integrative Neuroscience and Cognition Center, Paris, France. [2]Institut des Sciences Cognitives—Marc Jeannerod, UMR5229, CNRS and Université Claude Bernard Lyon 1, Bron, France. [3]École normale supérieure de Lyon, Lyon, France. [4]Université Claude Bernard Lyon 1, CNRS, INSERM, Centre de Recherche en Neurosciences de Lyon, U1028, UMR5292, Trajectoires, Bron, France. [5]Aix Marseille Université, CNRS, LPC, Marseille, France. e-mail: olivier.mascaro@gmail.com



Pattern	a Triadic pyramid	Triadic tree	b Transitive	Chain	Circular
Regulation of conflicts over resources	Regulated if the resources can be monopolized by A Otherwise, conflicts between B and C	Not regulated Conflicts between A and B	Regulated	Not regulated Conflicts between A and C	Not regulated Conflicts between A, B and C
Structural regularity (predicted by the conflict-regulatory hypothesis)	Pyramidal structure		Transitivity of relations		

Fig. 1 | Structural predictions based on the conflict-regulatory hypothesis. **a**, Overrepresentation of pyramids relative to trees. We posit that the cost of conflicts is downregulated more effectively by triadic pyramids than by triadic trees. Thus, if dominance mechanisms serve to lower the cost of conflicts, they should favour 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 downregulated in this structure (B and C yield to A, and C also yields to 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 downregulate the costs of conflicts, triadic transitive structures should be overrepresented in dominance networks, unlike circular and chain patterns.

two structures having similar complexities (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. By 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 downregulate the costs of conflicts, they should favour 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).

Dominance relations are characterized by their strong tendency to be transitive, and many dominance structures are completely linear[8,20,21]. 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[22–26]. Moreover, in many animal hierarchies, triadic pyramids are more frequent than in matched randomized networks[27,28]. There has been a long-standing debate on whether human and non-human hierarchies are similar and, if so, under what conditions[14,29–32]. 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[9,33–36]. When an individual cannot directly observe interactions, knowledge of a hierarchy's shape is key to guiding inferences about social relations[34,35,37–42]. For instance, dominance relations tend to be transitive: if A dominates B and B dominates C, then it is likely that A dominates C[20,34,43]. Humans—adults and infants—and several animal species exploit this structural regularity to draw transitive inferences about unobserved dominance relationships[44–49]. This capacity is remarkable because it involves spontaneous inferences akin to formal reasoning and does not appear to require teaching. Whereas 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_a and 1_b analysed 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_a, 5_b, 6_a, 6_b, 7_a and 7_b).

Results

The triadic-pyramidal shape of hierarchies

We compared the relative frequency of triadic pyramids with that of 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_a analysed the structure of children's social hierarchies and compared them with 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; >5,900 interactions, mean group size = 13.85, range of each group mean age = 13–74 months). We used data on children because they result from ethological observation, just like animal data. For animal data, we used a large archive of agonistic interactions from multiple species[50]. Data from 113 animal species fulfilled our study's inclusion criteria (298 groups; >166,241 interactions, mean group size = 14.71; Methods). In study 1_a, we grouped animal data by taxonomic category: primates, carnivores (Carnivora),

https://doi.org/10.1038/s41562-023-01634-5

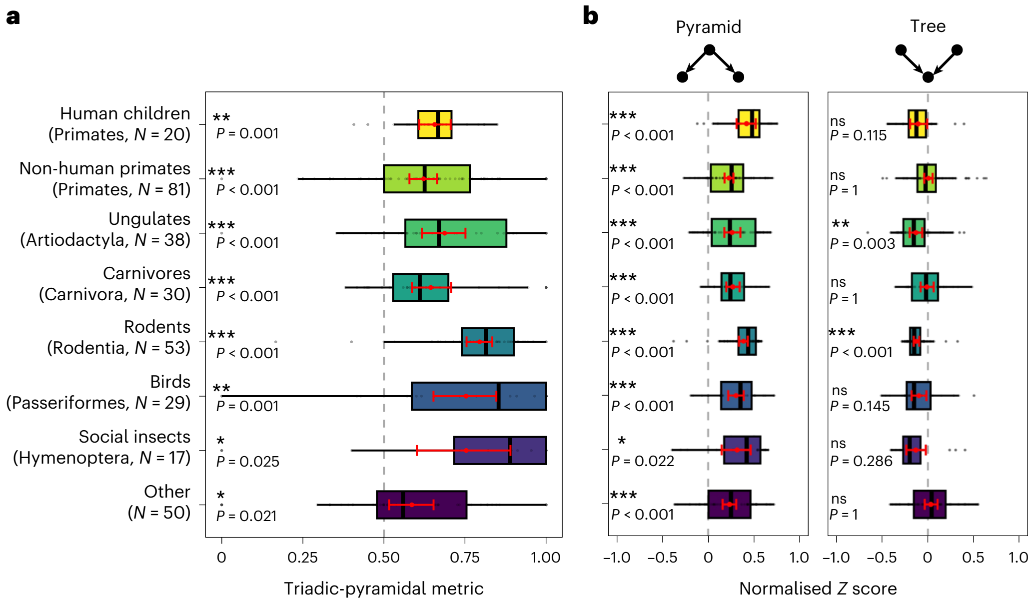


Fig. 2 | Assessment of pyramidal shape per taxonomic category ($N = 318$ independent groups). a, Triadic-pyramidal metric. **b**, Normalized Z scores for triadic pyramids and triadic trees. Dashed grey lines represent chance (0.5). Red dots and error bars indicate means and bootstrapped 95% CIs. Vertical bars within boxes indicate medians, and boxes indicate the interquartile range. 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.

rodents (Rodentia), ungulates (Artiodactyla), birds (Passeriformes), social insects (Hymenoptera) and other species (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, whereas the other individual was considered subordinate.

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

$$\text{Triadic-pyramidal metric} = \frac{N_{\text{pyramids}}}{N_{\text{pyramids}} + N_{\text{trees}}} \tag{1}$$

The average triadic-pyramidal metric was significantly higher than that predicted by chance in each taxonomic category (Fig. 2a, all P values < 0.05; see detailed statistics in Supplementary Tables 1–3), indicating that triadic pyramids are overrepresented in dominance networks.

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 with chance using simulations[28,51–53]. For each real network, we generated 1,000 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 (equation (2)) measuring the relative abundance of each triadic pattern in a real network compared with their frequency in simulated networks.

$$Z_i = \frac{\text{Nreal}_i - \text{Msim}_i}{\text{SDsim}_i} \tag{2}$$

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

These Z scores were normalized to obtain significance profiles (equation (3)) for comparison across groups of different sizes[51,54]. 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.

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

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[22–28]. Moreover, we found a comparable pyramidal motif in children. Average normalized Z scores were significantly higher for triadic pyramids than for triadic trees in children and in animals (all P values < 0.05; Supplementary Table 2). Moreover, average normalized Z scores for triadic pyramids were significantly higher than chance for all taxonomic groups (all P values < 0.05; Fig. 2b and Supplementary Table 3). Thus, triadic pyramids are more abundant in real dominance networks than in comparable randomized networks. By contrast, average normalized Z scores for triadic trees did not differ significantly from chance in any group except rodents and ungulates, in which 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 favour subordinate individuals when allocating resources increases over the kindergarten years (ages 3–6)[55–58]. Thus, we ran an additional analysis to evaluate the effect of age in children. This complementary analysis showed no detectable effect of age on the overrepresentation of triadic pyramids in children's dominance hierarchies (Supplementary Analysis).

Study 1_b used the same data as study 1_a 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 (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 that of the reference null model[59]. 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 (ΔDIC = −0.78 and ΔDIC = 1.47). For the all-species analysis, the model including phylogeny was a worse fit than the null model (ΔDIC = 14.62), and the model including network size did not improve upon the null model (ΔDIC = 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 λ, a measure of phylogenetic signal that varies between 0 (phylogenetic independence) and 1 (traits covary in direct proportion to species' shared evolutionary history)[60]. Pagel's λ estimates were close to zero both for the primate-only analysis ($M = 0.096$, mode = 0.018, 95% credible interval = 0.006–0.293) and for the all-species analysis ($M = 0.184$, mode = 0.094, 95% credible interval = 0.011–0.408).

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_a and 1_b. During the learning phase, participants memorized a network of social relations that included dominance and symmetric relationships (friendship in studies 2 and 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[61]. Moreover, ally networks are often organized hierarchically, and groups frequently dominate other groups[37,62]. 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 (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 analysed inferences regarding novel dominance relations to determine whether they were consistent with a pyramidal motif.

In two pilot studies (studies 1_a and 1_b, Supplementary Methods and Results), we ensured that participants drew systematic inferences about novel dominance relations by generalizing dominance across friendships (for example, after learning that A dominated B, participants inferred that A's friend dominated B's friend). In studies 2 and 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 (the 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 analysis of variance (ANOVA) on inference scores with the following factors: condition (pyramid versus tree; within participants in study 2, between participants in studies 3 and 4), gender of names (female versus male; between participants) and phrasing used to convey dominance (study 2 only: A dominates B versus B is dominated by A; between participants). These analyses were followed by one-sample t tests comparing average inference scores to chance (0.5; see detailed statistics in Supplementary Table 4).

In study 2, inference scores were significantly higher in the pyramid condition than in the tree condition (ANOVA, $F_{1,36} = 4.45$, $P = 0.042$, $\eta_p^2 = 0.11$, 95% confidence interval (CI) = [0.02, 1]). Other effects revealed by the ANOVA run on study 2's data are detailed in Supplementary Methods and Results. Inference scores were significantly higher than those predicted by chance in the pyramid condition ($t_{39} = 3.24$, $P = 0.005$, $d = 0.51$, 95% CI = [0.19, 0.96]), but not in the tree condition ($t_{39} = 0.68$, $P = 0.498$, $d = 0.11$, 95% CI = [−0.20, 0.42]) (Fig. 5b). Thus, participants inferred novel dominance relations following a triadic pyramid and not a triadic tree.

Whereas 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 (Methods). 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, (iii)).

For study 3, inference scores were significantly higher in the pyramid condition than in the tree condition (ANOVA, $F_{1,36} = 13.99$, $P < 0.001$, $\eta_p^2 = 0.28$, 95% CI = [0.09, 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; $t_{19} = 2.95$, $P = 0.016$, $d = 0.66$, 95% CI = [0.27, 1.11]) and significantly lower than chance in the tree condition ($t_{19} = -2.31$, $P = 0.032$, $d = -0.52$, 95% CI = [−1.43, −0.03]). 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[63]. 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, $F_{1,36} = 14.51$, $P < 0.001$, $\eta_p^2 = 0.29$, 95% CI = [0.1, 1]), and no other significant effects besides condition were revealed by the ANOVA. Additionally, inference scores were significantly higher than those predicted by chance in the pyramid condition (Fig. 5b; $t_{19} = 3.43$, $P = 0.006$, $d = 0.77$, 95% CI = [0.44, 1.25]), but not in the tree condition ($t_{19} = -1.80$, $P = 0.088$, $d = -0.40$, 95% CI = [−0.97, 0.04]). Thus, studies 3 and 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

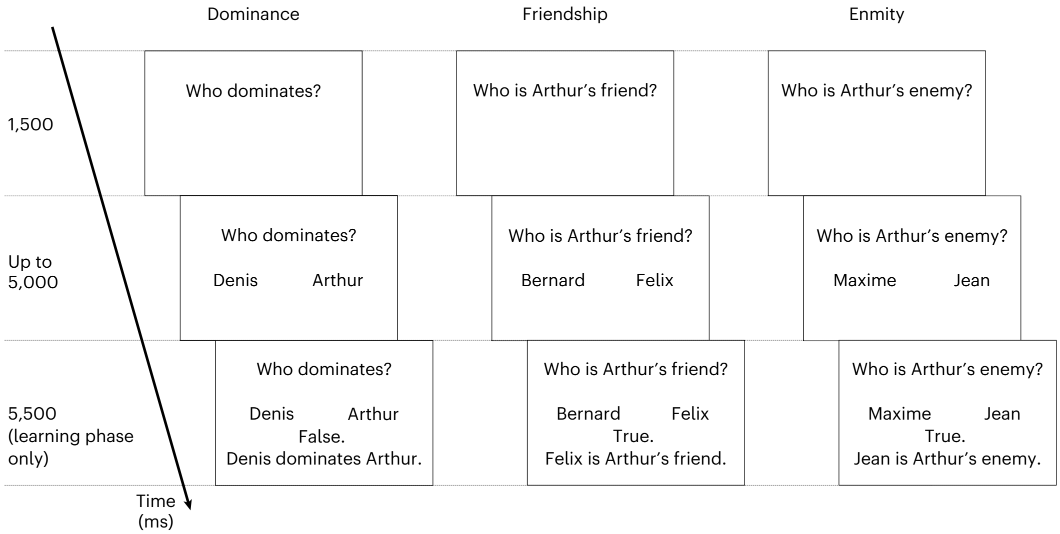


Fig. 3 | Timeline of trials testing adults on dominance, friendship or enmity relations. Each question was presented alone for 1.5 s. Next, two names appeared, and the participants had 5 s to choose one. During the learning phase, the participants received feedback on the accuracy of their answers for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

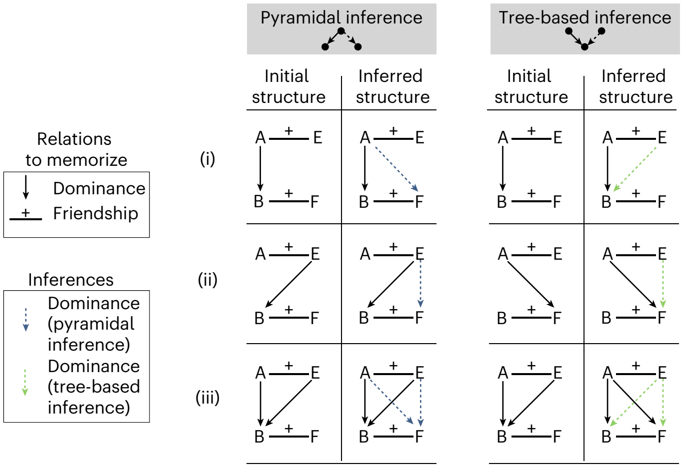


Fig. 4 | Examples of pyramidal and tree-based inferences. Each arrow represents a dominance relationship (pointing towards the subordinate agent). Line segments with a '+' on top represent friendships. Solid lines represent relations that participants had to memorize during the learning phase. Dashed lines represent novel dominance relations that can be inferred. (i) and (ii) 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). (iii) shows examples of inferences tested in study 3, which combines inferences illustrated in (i) and (ii).

experiments (studies 5_a, 5_b, 6_a, 6_b, 7_a and 7_b) 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 capitalized on previous research on infants' capacity to extract information about social relations[44,46,64–84].

In studies 5_a, 5_b, 6_a, 6_b, 7_a and 7_b, 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[85,86]. We tested 14-month-old infants because, by this age, infants' capacity to process information about dominance[44,66,68,69,73,75] and alliance[78–81,83,84] 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 and D), which were represented by 2D geometrical shapes with eyes, similar to many studies on social cognition in infants[46,66,71,73–75,80,87–90]. During the test phase, we assessed the infants' expectations of an unobserved dominance interaction. Studies 5_a and 5_b tested whether the infants generalized dominance across allies. Studies 6_a, 6_b, 7_a and 7_b tested whether their generalizations were consistent with the pyramidal motif observed in dominance networks (Fig. 6a).

In studies 5_a, 6_a and 7_a, the infants were familiarized with events designed to convey that A and B were allies, C and D were allies and A dominated C (Methods and Supplementary Video 1). The 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 centre 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 watched two test videos assessing their inferences about the dominance relations between two agents that were not shown to compete. The identities of the competing agents varied across the experiments. For instance, because study 5_a tested the capacity to generalize dominance across sets of allies, the test videos in study 5_a 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 (Supplementary Video 2). Once the competition ended, the screen froze and we measured looking time. For study 5_a, the infants were predicted to expect the dominant's ally to prevail over the subordinate's ally and, thus, to look longer at the incoherent events.

As controls for studies 5_a, 6_a and 7_a, studies 5_b, 6_b and 7_b tested the role of alliances in guiding how infants generalized dominance relations. The controls were identical to their respective studies, except that alliance information was made more ambiguous by changing the timing of actions (Supplementary Videos 3 and 4 and Fig. 6c). In the three controls, each agent responded to and moved along the same path as its partner agent located at 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.

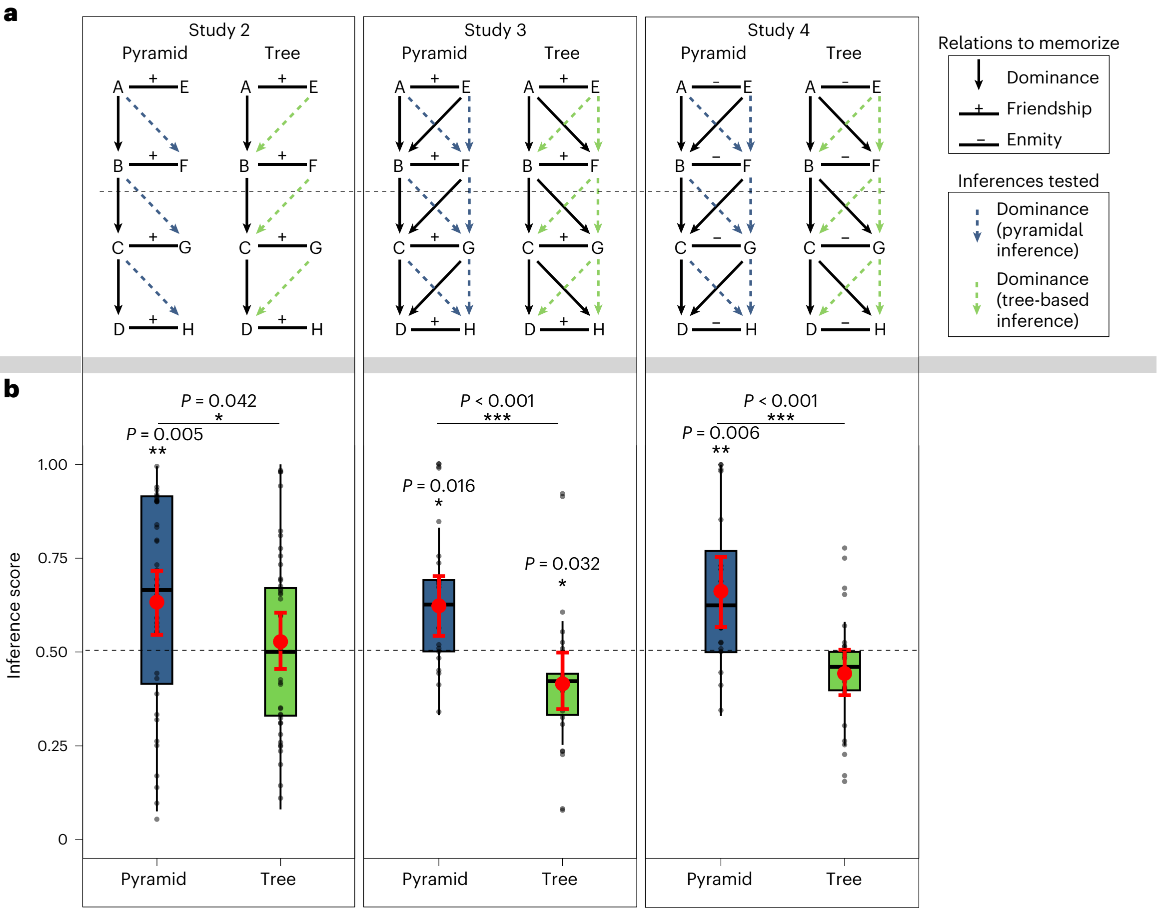


Fig. 5 | Network structures and results of studies 2–4. a, Schematic representation of social networks used in studies 2–4, per condition (pyramid versus tree). Each arrow represents a dominance relation (pointing towards the subordinate agent). Lines represent friendships ('+' on top) or enmity relations ('−' on top). Solid lines represent relations that participants memorized during the learning phase. Dashed lines represent novel relations for inference during the test phase, with the 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 (Fig. 3). **b**, Inference scores across studies 2–4 ($N = 40$ per study). The dashed grey line represents chance (0.5). Red dots and error bars indicate means and bootstrapped 95% CIs, respectively. Horizontal bars within boxes indicate medians, and boxes indicate the interquartile range. 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 versus tree) on inference scores was assessed using two-tailed full-factorial ANOVAs on inference scores with the following factors: condition (pyramid versus tree; within participants in study 2, between participants in studies 3 and 4), gender of names (female versus male; between participants) and phrasing used to convey dominance (study 2 only; A dominates B versus B is dominated by A; between participants). For each study, P values for comparisons of inference scores against chance were assessed using two-tailed one-sample t tests and were corrected for multiple comparisons across conditions using the Holm–Bonferroni procedure. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

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

In studies 5_a and 5_b, infants looked longer at incoherent than coherent test events (ANOVA, $F_{1,38} = 4.80$, $P = 0.035$, $\eta_p^2 = 0.11$, 95% CI = [0, 1]). The interaction between coherence and study was also significant ($F_{1,38} = 5.93$, $P = 0.020$, $\eta_p^2 = 0.13$, 95% CI = [0.01, 1]), revealing that the infants responded to situations differently, depending on the study. The infants in study 5_a looked significantly longer at the incoherent test events than at the coherent ones (Fig. 7a; $t_{19} = -3.12$, $P = 0.011$, $d = -0.70$, 95% CI = [−1.11, −0.35]), implying that they expected the dominant's ally to prevail over the subordinate's ally. Conversely, the infants in study 5_b did not differ in looking time between incoherent and coherent events, as expected when alliances were ambiguous (Fig. 7a; $t_{19} = 0.180$, $P = 0.858$, $d = 0.04$, 95% CI = [−0.46, 0.48]). Thus, information about alliances shaped infants' generalization of dominance relations across individuals.

Next, studies 6_a and 6_b investigated whether infant inferences in studies 5_a and 5_b were consistent with a triadic-pyramidal motif (Fig. 6a). These studies followed the same procedures as studies 5_a and 5_b, except that in the test videos of studies 6_a and 6_b, the dominant agent competed with the subordinate's ally (Supplementary Video 5). The dominant agent prevailed in the coherent test, whereas the ally of the subordinate agent prevailed in the incoherent test. Thus, studies 6_a and 6_b tested whether infants generalize dominance according to a triadic-pyramidal pattern.

In studies 6_a and 6_b, the interaction between test coherence and study was significant (ANOVA, $F_{1,38} = 6.03$, $P = 0.019$, $\eta_p^2 = 0.14$, 95% CI = [0.01, 1]). Thus, infants responded differently to events depending on the study. In study 6_a, infants looked significantly longer at incoherent than at coherent test events (Fig. 7b; $t_{19} = -3.29$, $P = 0.008$, $d = -0.74$, 95% CI = [−0.87, −0.29]), indicating an expectation that the dominant agent will prevail over the ally of its subordinates (pyramidal inference).

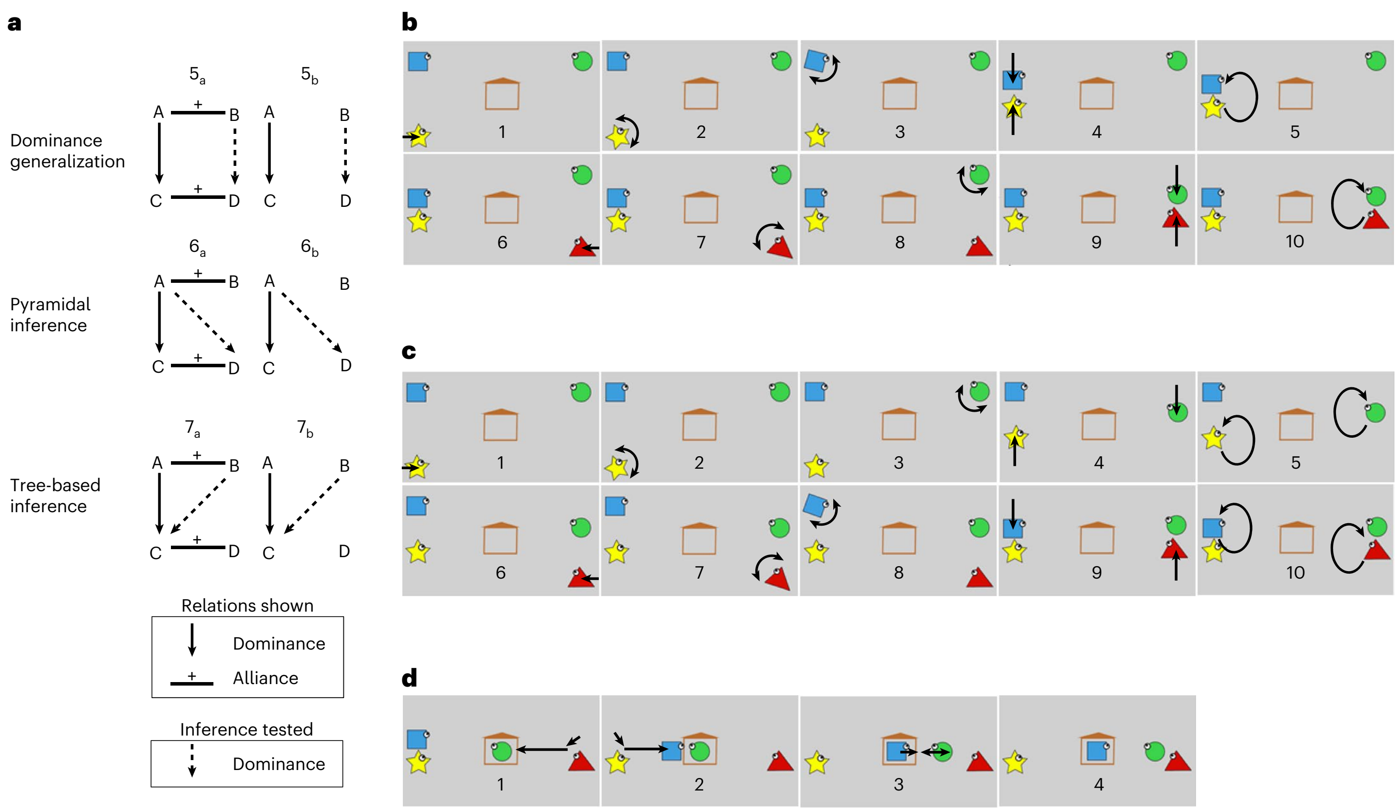


Fig. 6 | Network structures and events used in studies 5_a, 5_b, 6_a, 6_b, 7_a and 7_b. **a**, Schematic representation of social networks used in studies 5_a, 5_b, 6_a, 6_b, 7_a and 7_b. Each arrow represents a dominance relation (pointing towards the subordinate agent). Lines with a '+' on top represent alliances. Solid lines represent relations observed during familiarization videos. Dashed 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_a, 6_a and 7_a. **c**, Stills of videos conveying information about alliances in studies 5_b, 6_b and 7_b. **d**, Stills of videos conveying information about dominance in studies 5_a, 5_b, 6_a, 6_b, 7_a and 7_b.

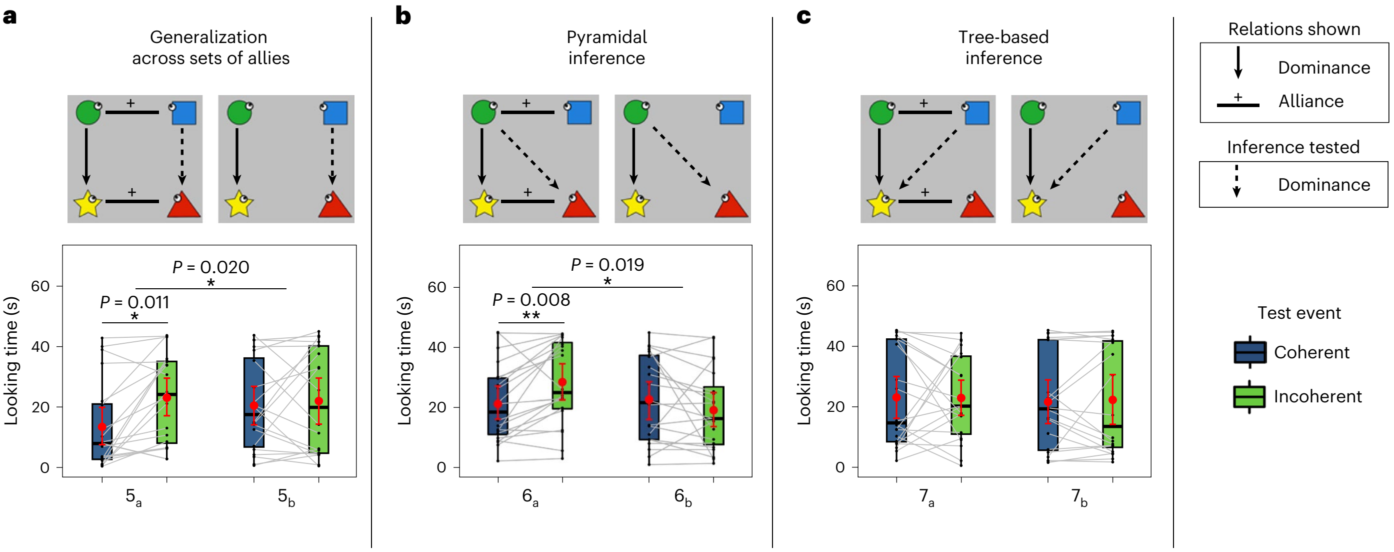


Fig. 7 | Looking time per situation (coherent versus incoherent) and study ($N = 20$ per study). **a**, Studies 5_a and 5_b. **b**, Studies 6_a and 6_b. **c**, Studies 7_a and 7_b. Red dots and error bars indicate means and bootstrapped 95% CIs. Horizontal bars within boxes indicate medians, and boxes indicate the interquartile range. 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 using full-factorial two-tailed ANOVAs on log-transformed looking time with test coherence (coherent versus incoherent) as a within-participant variable and study (5_a versus 5_b, 6_a versus 6_b, 7_a versus 7_b) as a between-participant variable. For each study, P values for the effect of coherence on looking time were assessed using two-tailed t tests for matched pairs and were corrected for multiple comparisons across pairs of studies (studies 5_a and 5_b, 6_a and 6_b, 7_a and 7_b) using the Holm–Bonferroni procedure $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

Additionally, test coherence had no detectable effect on looking time in study 6_b (Fig. 7b; $t_{19} = 0.99$, $P = 0.334$, $d = 0.22$, 95% CI = [−0.08, 0.72]), 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_a and 7_b (Fig. 6a). Whereas generally following the same procedures as studies 6_a and 6_b, studies 7_a and 7_b differed in showing test videos with the subordinate competing against the dominant's ally (Supplementary Video 6). 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_a and 7_b. As predicted, the two-way ANOVA revealed no significant effects. Moreover, follow-up analyses revealed no significant effect of test coherence on infants' looking time (Fig. 7c and Supplementary Table 5). 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[10–12,18,19].

Study 1_a confirms that transitive triads are also overrepresented in dominance hierarchies (Extended Data Fig. 1), in line with the literature[8,14,20]. 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, and transitive structures are predominant for triads with three relationships. Furthermore, 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[91,92]. 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).

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[14]. 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 with triadic trees. Structurally, this hypothesis can be implemented in two non-mutually exclusive ways. Triadic pyramids might be (1) more stable than trees and (2) 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. By 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.

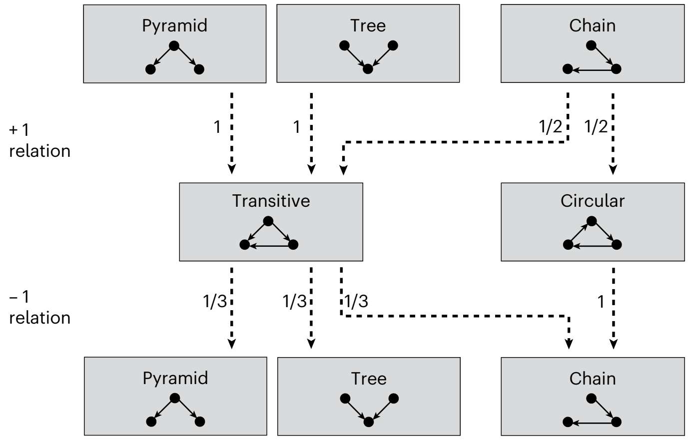


Fig. 8 | Transition probability graph for triadic structures with two or three relations. Each solid arrow represents a dominance relation (pointing towards the subordinate agent). Dashed arrows represent transitions from one structure to another. Numbers next to dashed arrows represent the transitional 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).

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[44,46,48,49]. 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 complexities. Research suggests that adults find hierarchies easy to process[49,93] and that they can rapidly determine dominance relations between individuals[94,95] or groups[96]. 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 behaviourally[34,97,98]. 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. By contrast, the pyramidal inferences that we studied appear probabilistic (that is, 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[99] and dominance hierarchies[100–102] before 2 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_a and 5_b), making inferences consistent with a pyramidal shape (studies 6_a and 6_b) and not with a tree-like shape (studies 7_a and 7_b). 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 those of other studies showing that infants combine information from two distinct relational domains: alliances and dominance[70,71].

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 forms requires navigating a vast hypothesis space[103,104]. 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, 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 and represent 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 written informed consent prior to the inclusion of the participants in the studies (except for studies 1_a and 1_b, which relied on data openly accessible from the literature). Adults enrolled in studies 2–4 received €10 as compensation for their participation. Families enrolled in studies 5_a, 5_b, 6_a, 6_b, 7_a and 7_b 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_a and 1_b

Datasets. Human data were obtained from a Google Scholar search performed in April 2021, using the following 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 centres (15 distinct groups). We also opportunistically added as many datasets as possible (five additional distinct groups). Studies were included if they reported data that showed either who won each of the observed conflicts or dominance relationships (that is, 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 Supplementary Table 6).

Animal data were obtained from DomArchive, a large database of agonistic interactions in multiple species[50]. 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 by 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, whereas the other individual 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, in which 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; Fig. 1). Statistical analyses were based on the distribution of triadic patterns.

Phylogenetic analyses. In study 1_b, we used Bayesian phylogenetic models to estimate the effects of group size and relatedness on the triadic-pyramidal metric. We used the '10KTrees' phylogeny to estimate relatedness among primates[105] 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 the analyses for this experiment (primates: *Cercocebus sanjei*; all species: *Sus scrofa*, *Pachycondyla* spp., *Eulemur fulvus*, *Gorilla gorilla*, *Pan troglodytes*).

When necessary, the phylogeny was made ultrametric, using non-negative least squares[106], then transformed into an inverted phylogenetic covariance matrix using the algorithm of Hadfield and Nakagawa[107]. This covariance matrix was added as a random effect in Bayesian phylogenetic mixed models, with the triadic-pyramidal metric as the dependent variable. We used uninformative priors ($V = 1$, nu = 0.002 (ref. 108)) with 13,000 iterations and a burn-in of 3,000.

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

Studies 2–4

Participants. The analysis included 120 participants across studies 2–4 (M_{age} = 22.88 years; range = 18–34 years; 65 women, N = 40 per study). The participants were recruited by sending announcements on several cognitive science mailing lists distributed in the Lyon area and by advertising the study on social media. All adult participants gave their written informed consent prior to their inclusion in the studies. The participants were randomly assigned to studies and conditions. Pyramid and tree conditions were tested within participants in study 2 and between participants in studies 3 and 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 in LCD monitor and responded using an AZERTY keyboard. Stimuli were presented on the monitor using MATLAB R2015b and the Psychophysics Toolbox[109]. Experimenters were not blinded to the 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 (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 (for example, "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 right or left arrow on the keyboard. For dominance relations, participants chose between the name of a dominant individual and that of its subordinate. For friendship and enmity, participants chose between the name 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 (for example, "[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, ten filler and six test trials in studies 3 and 4; Fig. 5a). For further details, see Supplementary Methods and Results.

Studies 5_a, 5_b, 6_a, 6_b, 7_a and 7_b

Participants. For these experiments, we included 120 healthy, full-term, 14-month-old infants in the analysis (M_{age} = 431 days; range = 389–468 days; 58 girls, N = 20 per 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 written informed 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 behaviour. Caregivers were instructed to close their eyes to avoid caregiver interference. Apart from the infants' caregivers, and the infants themselves, no one else was present in the testing room during the experiment. Experimenters were not blinded to the conditions, but monitored the experiment from a separate room. During the experiment, infants watched 2D animations generated using Synfig Studio (v.1.0). These animations involved four geometrical figures with eyes (representing agents): a blue square, a green circle, a red triangle and a yellow star. At the centre 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_a, 6_a and 7_a, infants first watched four 7 s warm-up videos showing each of the agents alone, moving towards the centre 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[46,66,68,80,81,110,111]. Long (22 s) and short (13 s) versions of the familiarization videos were used to alleviate boredom (Supplementary Video 7). In the long familiarization videos, alliances were conveyed by showing pairs of agents taking turns oscillating and emitting 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 centre 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. The short familiarization videos were identical to the long ones, except that the agents did not move together along a circular path. The familiarization videos were shown in the following order: long, short, short, and long. Next, infants watched two test movies probing their inferences about a novel dominance relation.

The test movies were identical to the short familiarization videos, except for the identity of the two competing agents. In study 5_a, the dominant's ally competed with the subordinate's ally. In study 6_a, the dominant competed with the subordinate's ally. In study 7_a, 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 watched a coherent and incoherent test event (the 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 behaviours during the test phase (see details about counterbalanced factors in Supplementary Methods and Results).

Studies 6_b, 7_b and 8_b were identical to studies 6_a, 7_a and 8_a, 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 oscillating and emitting 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_b, 7_b and 8_b, we labelled "coherent" the test events in which the dominant agent or the agent located on the dominant agent's side prevailed; we labelled "incoherent" the test events in which the other agents prevailed. See Supplementary Methods and Results for additional details regarding procedures and coding.

Analysis. Data were preprocessed and analysed 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 1,000 samples. To better approximate a normal distribution, infant looking-time data were log transformed[112]. However, descriptive statistics and plots feature untransformed looking-time data to ease interpretation.

Reporting summary

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

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.

References

1. Krieger, N. Ladders, pyramids and champagne: the iconography of health inequities. *J. Epidemiol. Community Health* **62**, 1098–1104 (2008).
2. Yu, S., Greer, L. L., Halevy, N. & Van Bunderen, L. On ladders and pyramids: hierarchy's shape determines relationships and performance in groups. *Personal. Soc. Psychol. Bull.* **45**, 1717–1733 (2019).
3. Gruenfeld, D. H. & Tiedens, L. Z. in *Handbook of Social Psychology* (eds Fiske, S. T. et al.) 1252–1287 (John Wiley and Sons, 2010).
4. Blau, P. M. A macrosociological theory of social structure. *Am. J. Sociol.* **83**, 26–54 (1977).
5. Wellman, N., Applegate, J. M., Harlow, J. & Johnston, E. W. Beyond the pyramid: alternative formal hierarchical structures and team performance. *Acad. Manag. J.* **63**, 997–1027 (2020).
6. Hand, J. L. Resolution of social conflicts: dominance, egalitarianism, spheres of dominance, and game theory. *Q. Rev. Biol.* **61**, 201–220 (1986).
7. Weber, M. in *From Max Weber: Essays in Sociology* (eds Gerth, H. H. and Wright Mills, C.) 180–195 (Oxford Univ. Press, 1946).
8. Strauss, E. D., Curley, J. P., Shizuka, D. & Hobson, E. A. The centennial of the pecking order: current state and future prospects for the study of dominance hierarchies. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **377**, 20200432 (2022).
9. Cummins, D. D. in *Encyclopedia of Evolutionary Psychological Science* (eds Shackelford, T. K. and Weekes-Shackelford, V. A.) 7923–7932 (Springer, 2016).
10. Hawley, P. H. The ontogenesis of social dominance: a strategy-based evolutionary perspective. *Dev. Rev.* **19**, 97–132 (1999).
11. Hawley, P. H. Ontogeny and social dominance: a developmental view of human power patterns. *Evol. Psychol.* **12**, 318–342 (2014).
12. Hawley, P. H. & Bower, A. R. in *Handbook of Peer Interactions, Relationships, and Groups* 106–122 (Guilford, 2018).
13. Cummins, D. D. in *Encyclopedia of Evolutionary Psychological Science* (eds Shackelford, T. K. and Weekes-Shackelford, V. A.) 41–44 (Springer, 2016).
14. Tibbetts, E. A., Pardo-Sanchez, J. & Weise, C. The establishment and maintenance of dominance hierarchies. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **377**, 20200450 (2022).
15. Flack, J. C. & Krakauer, D. C. Encoding power in communication networks. *Am. Nat.* **168**, E87–E102 (2006).
16. Smith, J. M. The theory of games and the evolution of animal conflicts. *J. Theor. Biol.* **47**, 209–221 (1974).
17. Smith, J. & Price, G. R. The logic of animal conflict. *Nature* **246**, 15–18 (1973).
18. Bernstein, I. S. Dominance: the baby and the bathwater. *Behav. Brain Sci.* **4**, 419–429 (1981).
19. Holekamp, K. E. & Strauss, E. D. Aggression and dominance: an interdisciplinary overview. *Curr. Opin. Behav. Sci.* **12**, 44–51 (2016).
20. Shizuka, D. & McDonald, D. B. A social network perspective on measurements of dominance hierarchies. *Anim. Behav.* **83**, 925–934 (2012).
21. Neumann, C., McDonald, D. B. & Shizuka, D. Dominance ranks, dominance ratings and linear hierarchies: a critique. *Anim. Behav.* **144**, e1–e16 (2018).
22. Deslippe, R. J., M'Closkey, R. T., Dajczak, S. P. & Szpak, C. P. A quantitative study of the social behavior of tree lizards, *Urosaurus ornatus*. *J. Herpetol.* **24**, 337–341 (1990).
23. Uhrich, J. The social hierarchy in albino mice. *J. Comp. Psychol.* **25**, 373–413 (1938).
24. van Hooff, J. A. R. A. M. & Wensing, J. A. B. in *Man and Wolf: Advances, Issues, and Problems in Captive Wolf Research* (ed. Frank, H.) 219–252 (Dr W Junk Publishers, 1987).
25. Van Doorn, A. & Heringa, J. The ontogeny of a dominance hierarchy in colonies of the bumblebee *Bombus terrestris* (Hymenoptera, Apidae). *Insectes Soc.* **33**, 3–25 (1986).
26. Kinsey, K. P. Social behaviour in confined populations of the Allegheny woodrat, *Neotoma floridana magister*. *Anim. Behav.* **24**, 181–187 (1976).
27. Shimoji, H., Abe, M. S., Tsuji, K. & Masuda, N. Global network structure of dominance hierarchy of ant workers. *J. R. Soc. Interface* **11**, 20140599 (2014).
28. Shizuka, D. & McDonald, D. B. The network motif architecture of dominance hierarchies. *J. R. Soc. Interface* **12**, 20150080 (2015).
29. Chen Zeng, T., Cheng, J. T. & Henrich, J. Dominance in humans. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **377**, 20200451 (2022).
30. Chase, I. D. Social process and hierarchy formation in small groups: a comparative perspective. *Am. Sociol. Rev.* **45**, 905–924 (1980).
31. Redhead, D. & Power, E. A. Social hierarchies and social networks in humans. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **377**, 20200440 (2022).
32. Dubreuil, B. *Human Evolution and the Origins of Hierarchies: The State of Nature* (Cambridge Univ. Press, 2010).
33. Thomsen, L. & Carey, S. in *Navigating the Social World: What Infants, Children, and Other Species Can Teach Us* (eds Banaji, M. R. and Gelman, S. A.) 17–22 (Oxford Univ. Press, 2013).
34. Fiske, A. P. *Structures of Social Life: The Four Elementary Forms of Human Relations: Communal Sharing, Authority Ranking, Equality Matching, Market Pricing* (Free Press, 1991).
35. Fiske, A. P. The four elementary forms of sociality: framework for a unified theory of social relations. *Psychol. Rev.* **99**, 689–783 (1992).
36. Cheney, D. L. & Seyfarth, R. M. *Baboon Metaphysics* (Univ. Chicago Press, 2008).
37. Bergman, T. J., Beehner, J. C., Cheney, D. L. & Seyfarth, R. M. Hierarchical classification by rank and kinship in baboons. *Science* **302**, 1234–1236 (2003).
38. Basyouni, R. & Parkinson, C. Mapping the social landscape: tracking patterns of interpersonal relationships. *Trends Cogn. Sci.* **26**, 204–221 (2022).

39. Cummins, D. D. How the social environment shaped the evolution of mind. *Synthese* **122**, 3–28 (2000).
40. Cummins, D. D. Dominance hierarchies and the evolution of human reasoning. *Minds Mach.* **6**, 463–480 (1996).
41. Fernald, R. D. Cognitive skills and the evolution of social systems. *J. Exp. Biol.* **220**, 103–113 (2017).
42. Cummins, D. D. in *Encyclopedia of Evolutionary Psychological Science* (eds Shackelford, T. K. and Weekes-Shackelford, V. A.) 2104–2112 (Springer, 2016).
43. Strayer, F. F. & Strayer, J. An ethological analysis of social agonism and dominance relations among preschool children. *Child Dev.* **47**, 980–989 (1976).
44. Gazes, R. P., Hampton, R. R. & Lourenco, S. F. Transitive inference of social dominance by human infants. *Dev. Sci.* **20**, e12367 (2017).
45. Grosenick, L., Clement, T. S. & Fernald, R. D. Fish can infer social rank by observation alone. *Nature* **445**, 429–432 (2007).
46. Mascaro, O. & Csibra, G. Human infants' learning of social structures: the case of dominance hierarchy. *Psychol. Sci.* **25**, 250–255 (2014).
47. Paz-y-Miño, C. G., Bond, A. B., Kamil, A. C. & Balda, R. P. Pinyon jays use transitive inference to predict social dominance. *Nature* **430**, 778–781 (2004).
48. De Soto, C. B. Learning a social structure. *J. Abnorm. Soc. Psychol.* **60**, 417–421 (1960).
49. Zitek, E. M. & Tiedens, L. Z. The fluency of social hierarchy: the ease with which hierarchical relationships are seen, remembered, learned, and liked. *J. Pers. Soc. Psychol.* **102**, 98–115 (2012).
50. Strauss, E. D. et al. DomArchive: a century of published dominance data. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **377**, 20200436 (2022).
51. Milo, R. et al. Network motifs: simple building blocks of complex networks. *Science* **298**, 824–827 (2002).
52. Stone, L., Simberloff, D. & Artzy-Randrup, Y. Network motifs and their origins. *PLoS Comput. Biol.* **15**, e1006749 (2019).
53. Farine, D. R. A guide to null models for animal social network analysis. *Methods Ecol. Evol.* **8**, 1309–1320 (2017).
54. Milo, R. et al. Superfamilies of evolved and designed networks. *Science* **303**, 1538–1542 (2004).
55. Cheng, N., Wan, Y., An, J., Gummerum, M. & Zhu, L. Power grabbed or granted: children's allocation of resources in social power situations. *J. Exp. Child Psychol.* **210**, 105192 (2021).
56. Zhang, X. et al. Material and relational asymmetry: the role of receivers' wealth and power status in children's resource allocation. *J. Exp. Child Psychol.* **208**, 105147 (2021).
57. Charafeddine, R. et al. Children's allocation of resources in social dominance situations. *Dev. Psychol.* **52**, 1843–1857 (2016).
58. Enright, E. A., Alonso, D. J., Lee, B. M. & Olson, K. R. Children's understanding and use of four dimensions of social status. *J. Cogn. Dev.* **21**, 573–602 (2020).
59. Spiegelhalter, D. J., Best, N. G., Carlin, B. P. & Van Der Linde, A. Bayesian measures of model complexity and fit. *J. R. Stat. Soc. Ser. B Stat. Methodol.* **64**, 583–639 (2002).
60. Pagel, M. Inferring the historical patterns of biological evolution. *Nature* **401**, 877–884 (1999).
61. Verbrugge, L. M. The structure of adult friendship choices. *Soc. Forces* **56**, 576–597 (1977).
62. Pratto, F., Sidanius, J. & Levin, S. Social dominance theory and the dynamics of intergroup relations: taking stock and looking forward. *Eur. Rev. Soc. Psychol.* **17**, 271–320 (2006).
63. Hartup, W. W. & Abecassis, M. in *Blackwell Handbook of Childhood Social Development* (eds Smith, P. K. and Hart, C. H.) 286–306 (Blackwell, 2002).
64. Bas, J. & Sebastian-Galles, N. Infants' representation of social hierarchies in absence of physical dominance. *PLoS ONE* **16**, e0245450 (2021).
65. Enright, E. A., Gweon, H. & Sommerville, J. A. 'To the victor go the spoils': infants expect resources to align with dominance structures. *Cognition* **164**, 8–21 (2017).
66. Mascaro, O. & Csibra, G. Representation of stable social dominance relations by human infants. *Proc. Natl Acad. Sci. USA* **109**, 6862–6867 (2012).
67. Margoni, F., Baillargeon, R. & Surian, L. Infants distinguish between leaders and bullies. *Proc. Natl Acad. Sci. USA* **115**, E8835–E8843 (2018).
68. Meng, X., Nakawake, Y., Nitta, H., Hashiya, K. & Moriguchi, Y. Space and rank: infants expect agents in higher position to be socially dominant. *Proc. R. Soc. Lond. B Biol. Sci.* **286**, 20191674 (2019).
69. Meng, X. et al. Preverbal infants expect agents exhibiting counterintuitive capacities to gain access to contested resources. *Sci. Rep.* **11**, 10884 (2021).
70. Pun, A., Birch, S. A. & Baron, A. S. The power of allies: infants' expectations of social obligations during intergroup conflict. *Cognition* **211**, 104630 (2021).
71. Pun, A., Birch, S. A. & Baron, A. S. Infants use relative numerical group size to infer social dominance. *Proc. Natl Acad. Sci. USA* **113**, 2376–2381 (2016).
72. Pun, A., Birch, S. A. & Baron, A. S. Infants infer third-party social dominance relationships based on visual access to intergroup conflict. *Sci. Rep.* **12**, 18250 (2022).
73. Thomas, A. J. & Sarnecka, B. W. Infants choose those who defer in conflicts. *Curr. Biol.* **29**, 2183–2189 (2019).
74. Thomas, A. J., Thomsen, L., Lukowski, A. F., Abramyan, M. & Sarnecka, B. W. Toddlers prefer those who win but not when they win by force. *Nat. Hum. Behav.* **2**, 662–669 (2018).
75. Thomsen, L., Frankenhuis, W. E., Ingold-Smith, M. & Carey, S. Big and mighty: preverbal infants mentally represent social dominance. *Science* **331**, 477–480 (2011).
76. Bian, L., Sloane, S. & Baillargeon, R. Infants expect ingroup support to override fairness when resources are limited. *Proc. Natl Acad. Sci. USA* **115**, 2705–2710 (2018).
77. Jin, K. & Baillargeon, R. Infants possess an abstract expectation of ingroup support. *Proc. Natl Acad. Sci. USA* **114**, 8199–8204 (2017).
78. Liberman, Z., Kinzler, K. D. & Woodward, A. L. Friends or foes: infants use shared evaluations to infer others' social relationships. *J. Exp. Psychol. Gen.* **143**, 966–971 (2014).
79. Liberman, Z., Woodward, A. L., Sullivan, K. R. & Kinzler, K. D. Early emerging system for reasoning about the social nature of food. *Proc. Natl Acad. Sci. USA* **113**, 9480–9485 (2016).
80. Powell, L. J. & Spelke, E. S. Preverbal infants expect members of social groups to act alike. *Proc. Natl Acad. Sci. USA* **110**, E3965–E3972 (2013).
81. Powell, L. J. & Spelke, E. S. Human infants' understanding of social imitation: inferences of affiliation from third party observations. *Cognition* **170**, 31–48 (2018).
82. Rhodes, M., Hetherington, C., Brink, K. & Wellman, H. M. Infants' use of social partnerships to predict behavior. *Dev. Sci.* **18**, 909–916 (2015).
83. Thomas, A. J., Saxe, R. & Spelke, E. S. Infants infer potential social partners by observing the interactions of their parent with unknown others. *Proc. Natl Acad. Sci. USA* **119**, e2121390119 (2022).
84. Thomas, A. J., Woo, B., Nettle, D., Spelke, E. & Saxe, R. Early concepts of intimacy: young humans use saliva sharing to infer close relationships. *Science* **375**, 311–315 (2022).
85. Aslin, R. N. Infant eyes: a window on cognitive development. *Infancy* **17**, 126–140 (2012).
86. Stahl, A. E. & Feigenson, L. Observing the unexpected enhances infants' learning and exploration. *Science* **348**, 91–94 (2015).

87. Hamlin, J. K., Wynn, K. & Bloom, P. Social evaluation by preverbal infants. *Nature* **450**, 557–559 (2007).
88. Kanakogi, Y. et al. Third-party punishment by preverbal infants. *Nat. Hum. Behav.* **6**, 1234–1242 (2022).
89. Kanakogi, Y. et al. Preverbal infants affirm third-party interventions that protect victims from aggressors. *Nat. Hum. Behav.* **1**, 0037 (2017).
90. Kominsky, J. F., Lucca, K., Thomas, A. J., Frank, M. C. & Hamlin, J. K. Simplicity and validity in infant research. *Cogn. Dev.* **63**, 101213 (2022).
91. Chase, I. D. Dynamics of hierarchy formation: the sequential development of dominance relationships. *Behaviour* **80**, 218–240 (1982).
92. Chase, I. D. The sequential analysis of aggressive acts during hierarchy formation: an application of the 'jigsaw puzzle' approach. *Anim. Behav.* **33**, 86–100 (1985).
93. Zitek, E. M. & Phillips, L. T. Ease and control: the cognitive benefits of hierarchy. *Curr. Opin. Psychol.* **33**, 131–135 (2020).
94. Moors, A. & De Houwer, J. Automatic processing of dominance and submissiveness. *Exp. Psychol.* **52**, 296–302 (2005).
95. Ko, S. J., Sadler, M. S. & Galinsky, A. D. The sound of power: conveying and detecting hierarchical rank through voice. *Psychol. Sci.* **26**, 3–14 (2015).
96. Phillips, L. T., Slepian, M. L. & Hughes, B. L. Perceiving groups: the people perception of diversity and hierarchy. *J. Personal. Soc. Psychol.* **114**, 766–785 (2018).
97. Pietraszewski, D. How the mind sees coalitional and group conflict: the evolutionary invariances of n-person conflict dynamics. *Evol. Hum. Behav.* **37**, 470–480 (2016).
98. Pietraszewski, D. Toward a computational theory of social groups: a finite set of cognitive primitives for representing any and all social groups in the context of conflict. *Behav. Brain Sci.* **45**, e97 (2021).
99. Plusquellec, P., François, N., Boivin, M., Perusse, D. & Tremblay, R. E. Dominance among unfamiliar peers starts in infancy. *Infant Ment. Health J.* **28**, 324–343 (2007).
100. Strayer, F. F. & Trudel, M. Developmental changes in the nature and function of social dominance among young children. *Ethol. Sociobiol.* **5**, 279–295 (1984).
101. Russon, A. E. & Waite, B. E. Patterns of dominance and imitation in an infant peer group. *Ethol. Sociobiol.* **12**, 55–73 (1991).
102. Hawley, P. H. & Little, T. D. On winning some and losing some: a social relations approach to social dominance in toddlers. *Merrill-Palmer Q.* **45**, 185–214 (1999).
103. Tenenbaum, J. B., Kemp, C., Griffiths, T. L. & Goodman, N. D. How to grow a mind: statistics, structure, and abstraction. *Science* **331**, 1279–1285 (2011).
104. Kemp, C. & Tenenbaum, J. B. The discovery of structural form. *Proc. Natl Acad. Sci. USA* **105**, 10687–10692 (2008).
105. Arnold, C., Matthews, L. J. & Nunn, C. L. The 10kTrees website: a new online resource for primate phylogeny. *Evol. Anthropol. Issues N. Rev.* **19**, 114–118 (2010).
106. Revell, L. J. phytools: an R package for phylogenetic comparative biology (and other things). *Methods Ecol. Evol.* **3**, 217–223 (2012).
107. Hadfield, J. D. & Nakagawa, S. General quantitative genetic methods for comparative biology: phylogenies, taxonomies and multi-trait models for continuous and categorical characters. *J. Evol. Biol.* **23**, 494–508 (2010).
108. Hadfield, J. D. MCMC methods for multi-response generalized linear mixed models: the MCMCglmm R Package. *J. Stat. Softw.* **33**, 1–22 (2010).
109. Brainard, D. H. The psychophysics toolbox. *Spat. Vis.* **10**, 433–436 (1997).
110. Krupenye, C. & Hare, B. Bonobos prefer individuals that hinder others over those that help. *Curr. Biol.* **28**, 280–286 (2018).
111. Bas, J., Sebastian-Galles, N., Csibra, G. & Mascaro, O. Infants' representation of asymmetric social influence. *J. Exp. Child Psychol.* **226**, 105564 (2023).
112. Csibra, G., Hernik, M., Mascaro, O., Tatone, D. & Lengyel, M. Statistical treatment of looking-time data. *Dev. Psychol.* **52**, 521–536 (2016).

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 the Laboratory on Language, Brain and Cognition (L2C2) and of the Integrative Neuroscience and Cognition Center (INCC) for their invaluable input at all stages of this research. This work was supported by a fellowship from the French National Research Agency (ANR) to O.M. (Foundtrust, ANR-21-CE28-0017). The funders had no role in study design, data collection and analysis, the decision to publish or the preparation of the manuscript.

Author contributions

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

Competing interests

The authors declare no competing interests.

Additional information

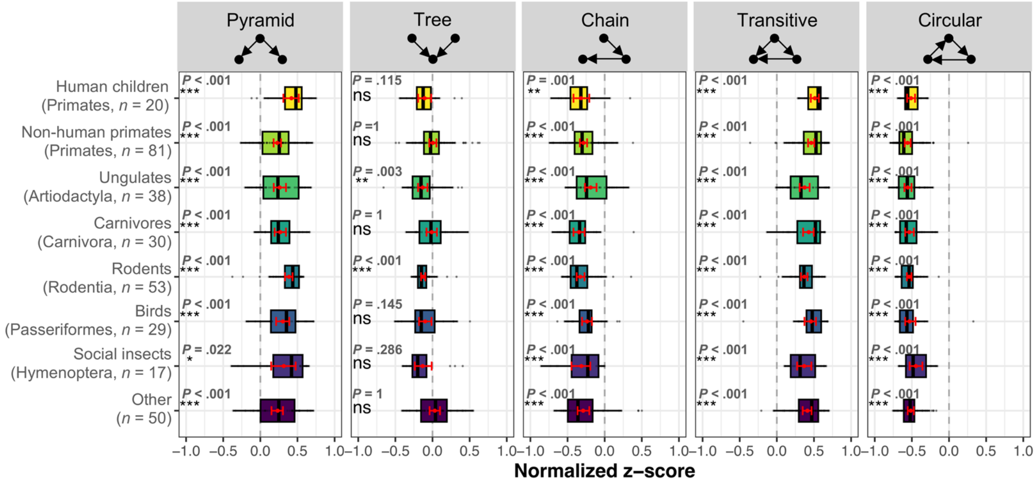
Extended data is available for this paper at https://doi.org/10.1038/s41562-023-01634-5.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41562-023-01634-5.

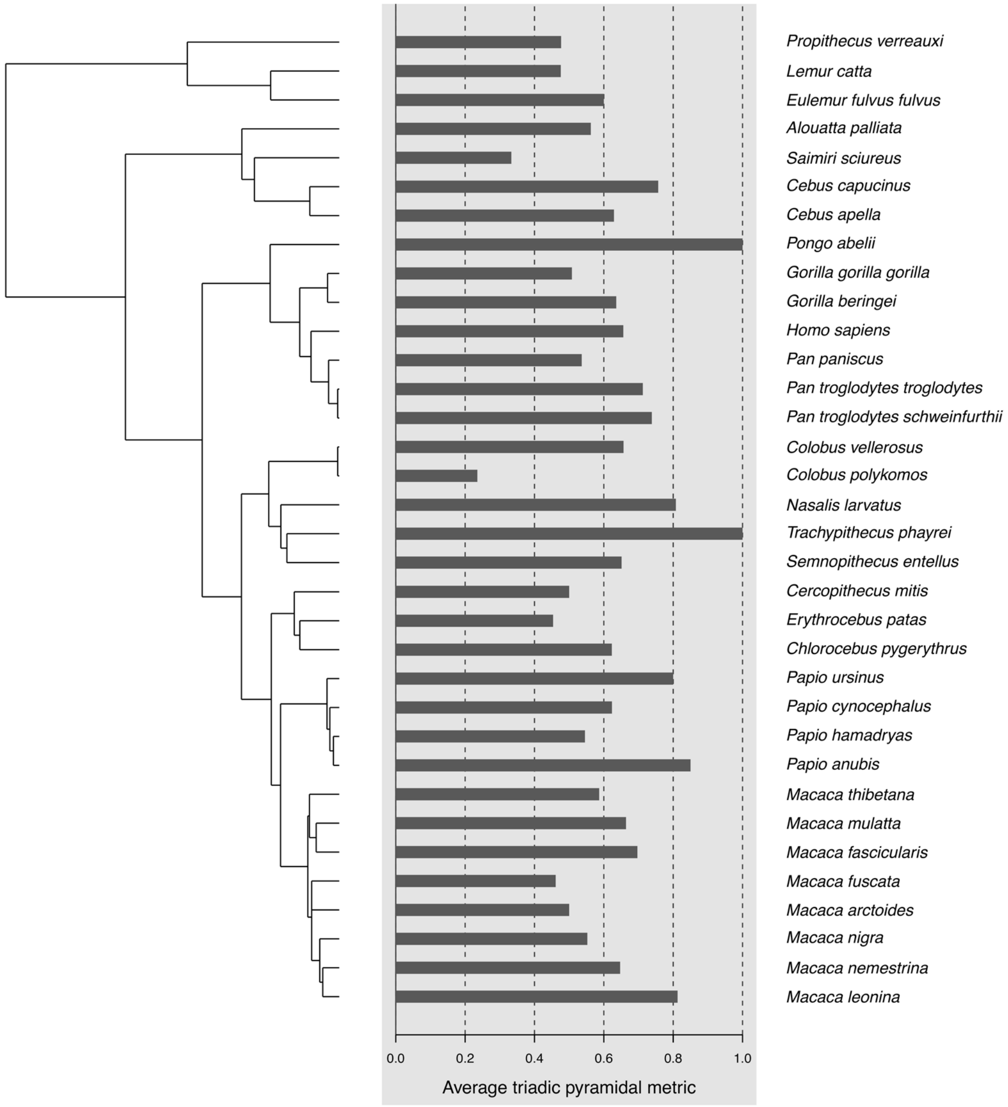
Correspondence and requests for materials should be addressed to Olivier Mascaro.

Peer review information *Nature Human Behaviour* thanks Denise D. Cummins and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Peer reviewer reports are available.

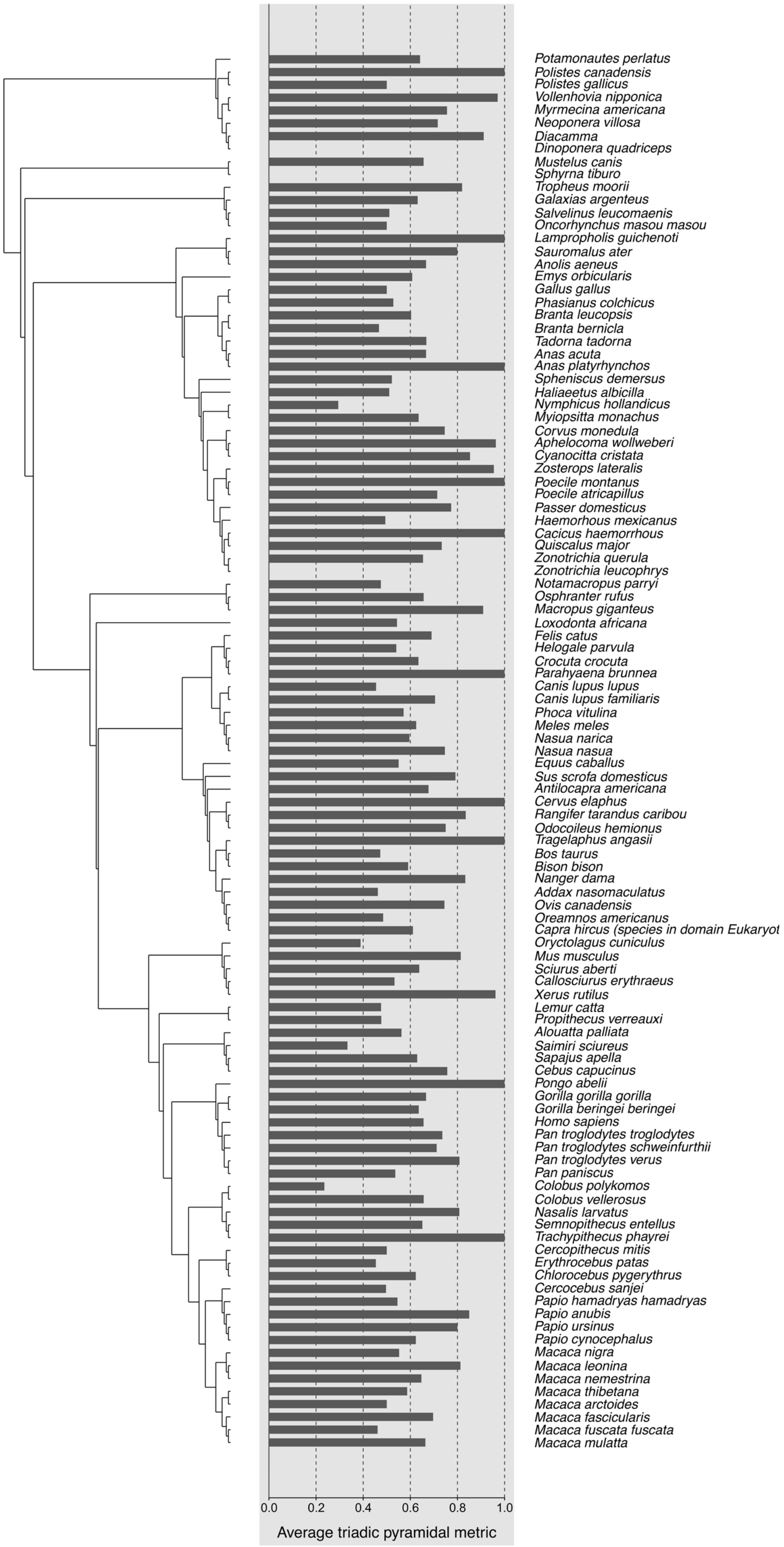
Reprints and permissions information is available at www.nature.com/reprints.



Extended Data Fig. 1 | Normalized z-scores per triadic pattern and category (N = 318 independent groups). We computed normalized z-scores for basic patterns that can occur in a dominance structure: triadic pyramids, triadic trees, chains, transitive triads, and circular triads. Data reveal a pyramidal motif, with an overrepresentation of pyramids in all taxonomic groups. The results also confirm that dominance relations tend to be transitive in all taxonomic groups, with an overrepresentation of transitive structures and an under-representation of chains and circular structures. Red dots and error bars indicate means and bootstrapped 95% CIs; vertical bars within boxes indicate medians, and boxes indicate the interquartile range; 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 categories using the Holm-Bonferroni procedure. * $p < .05$, ** $p < 0.01$, *** $p < 0.001$, ns: non-significant.



Extended Data Fig. 2 | Average triadic pyramidal metric per species organized by phylogeny for primates species only (36 species, 100 groups). We used the "10kTrees" phylogeny to estimate relatedness among primates[105].



Extended Data Fig. 3 | Average triadic pyramidal metric per species organized by phylogeny for all species (110 species, 311 groups). We used 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 species.

nature portfolio

Corresponding author(s): Olivier Mascaro
Last updated by author(s): Jan 10, 2023

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☐	☒	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☒	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	For Studies 2-4, stimuli were presented using MATLAB R2015b and the Psychophysics Toolbox (v.3.0.11). For Studies 5ab-7ab, stimuli were generated with Synfig Studio (v.1.0) and presented using Keynote(v.12.2). For Studies 5ab-7ab, data were coded using Anvil (v.5). For the other studies, no software was used for data collection.
Data 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). The analysis codes are shared publicly on OSF (https://doi.org/10.17605/OSF.IO/PK7BG).

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

All data are publicly available on OSF (https://doi.org/10.17605/OSF.IO/PK7BG). For the structural analysis of animal hierarchies, we used publicly available data from domArchive (https://github.com/DomArchive/DomArchive)

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	Participants' gender per Study : Study S1a: n = 20 (11 females, 9 males); Study S1b: n = 20 (11 females, 9 males); Study 2: n = 40 (21 females, 19 males); Study 3, pyramidal condition: n = 20 (12 females, 8 males); Study 3, tree condition: n = 20 (10 females, 10 males); Study 4 pyramidal condition: n = 20 (11 females, 9 males); Study 4 tree condition: n = 20 (11 females, 9 males); Study 5a: n = 20 (9 females, 11 males); Study 5b: n = 20 (10 females, 10 males); Study 6a: n = 20 (10 females, 10 males); Study 6b: n = 20 (9 females, 11 males); Study 7a: n = 20 (9 females, 11 males); Study 7b: n = 20 (11 females, 9 males). Gender was reported based on self-reporting (for adult participants), and based on caregiver's reporting (for infants). The gender of each participant is reported in the raw data available in the Supplementary Materials. We did not perform gender-based analyses because we had no hypothesis about the effect of gender on the type of inferences that we tested.
Population characteristics	See below.
Recruitment	Studies S1ab, 2, 3, 4: The adult 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. One possible slight selection bias in our sample might result from the fact that participants were recruited using online advertisement — thus, they needed to have direct or indirect access to a computer or a mobile phone. We doubt that this putative selection bias might have influenced our results, given that we tested adults' processing of sets of basic social relations. Studies 5ab,6ab,7ab: The infant participants were recruited using a procedure that is commonly used in infancy research centers. We sent letters to a randomly selected sample of children born in the Lyon and Paris areas, whose population are urban and of mixed socio-economic background. Typically, about 5% of the families receiving our invitation letter contact us to participate in a study. Out of these 5%, the overwhelming majority of families eventually participate in our studies. Occasionally, some families refuse to participate to studies involving exposure to screens. One possible selection bias in our sample of infants might result from the fact that participating families needed to be available during our lab opening hours (Monday to Saturday, 8 am- 6pm). We have no reason to assume that this putative selection bias might have influenced our results, given that we tested infants' processing of sets of basic social relations.
Ethics oversight	CPP Sud-Est II, IRB: 00009118

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Studies 1ab : observational data, quantitative ; Studies 2-4; 5ab-6ab-7ab: experimental, quantitative
Research sample	Studies 1ab: Children data: observational data from the literature (metadata is reported in details in table S6); we chose to analyze data from dominance interactions between children because they can be measured through ethological observations — just like non-human animal dominance interactions; we collected all the data that we could find on children's dominance matrices in the academic literature; thus, our sample is representative of available ethological data on children's dominance networks.

Non-human animal data: observational data from the literature (DomArchive, Strauss et al., 2022; metadata is available from the DomArchive database; https://doi.org/10.1098/rstb.2020.0436). We chose data from the DomArchive database because, to our knowledge, it is the most comprehensive database of agonistic interactions in non-human animal groups; it gathers data from a large set of studies and covers a wide range of species. This sample is representative of available ethological data on non-human animal agonistic interactions.

Studies S1ab, 2, 3, 4: 160 adults from a large French urban area (Lyon) were included in studies testing human adults' inferences (Study S1a: n = 20; mean age = 22.1 y; range = 19–28 y, 11 females; Study S1b: 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). We chose to test human adults because we were focusing on human's capacity to make inferences about unobserved dominance relations. Our sample is representative of a population of young adults living in a large French urban area.

Studies 5ab,6ab,7ab: We included 20 infants from a large urban area per Study (Study 5a: mean age = 433 d; range = 389–463 d, 9 females; Study 5b: mean age = 426 d; range = 391–456 d, 10 females; Study 6a: mean age = 433 d; range = 400–466 d, 10 females; Study 6b: mean age = 429 d; range = 399–460 d, 9 females; Study 7a: mean age = 430 d; range = 400–460 d, 9 females; Study 7b: mean age = 433 d; range = 400–468 d, 11 females). We chose to test infants because we were focusing on the early ontogeny of expectations about the shape of dominance hierarchies, before any explicit teaching about pyramidal structures can take place. We tested 14-month-old infants because by this age infants' capacity to process information about dominance and alliance relations is well-established. Our sample is representative of a population of 14-month-old infants living in a large French city.

Sampling strategy

Studies 1ab: Human data were obtained from a Google Scholar search performed during April 2021, using the 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. We also opportunistically added as many datasets as possible. Studies were included if it 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). If an article reported longitudinal data from the same group, we only used data collected at the first time point. 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. We excluded networks in which all individuals were directly connected by dominance relations, because triadic pyramids and triadic trees cannot occur in such networks. When repeated measurements were reported for the same group of animals, we kept only the first reported measure in the analysis.

We used a random sampling procedure for all experimental studies (S1ab, 2, 3, 4, 5ab, 6ab, 7ab).

Studies S1ab, 2, 3, 4: Although no study tested the pyramidal inference that we investigated, past studies testing adults' participants to the structural regularities of dominance structures typically show large effect sizes (De Soto, 1960; Zitek & Tiedens, 2012). An a priori power analysis performed with G*power3 (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 (α = .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.

Studies 5ab,6ab,7ab: An a priori power analysis performed with G*power3 (v.3.1), assuming an effect size of .667 (the mean effect size typically observed in looking time studies with infants, see Csibra et al., 2016) , 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 (α = .05).

Data collection

Studies 1ab : N/A. We did not collect novel data for Studies 1ab. For human data, we reanalyzed published data on children dominance matrices (see metadata in Table S6). For animal data, we analyzed data from DomArchive, a large database of agonistic interactions in multiple species (https://doi.org/10.1098/rstb.2020.0436).

Studies S1ab, 2, 3, 4: Adults were tested in a quiet room. Participants' responses were recorded using a computer using MATLAB R2015b and the Psychophysics Toolbox. No one was present in the testing room during the experiment besides the participant.
Studies 5ab,6ab,7ab: Infants were tested in a dimly lit and soundproof room, seated on their caregiver's lap ~70 cm from a 24-inch LCD monitor. Caregivers were instructed to close their eyes to avoid parental interference. A hidden camera mounted above the screen recorded infants' looking behavior. Apart from the infant caregiver, and the infant themselves, no one else was present in the testing room during the experiment. The researcher monitored the experiment from a separate room. Data collection was not performed blind to the conditions of the experiments. For each study measuring looking time, one of the co-authors, served as primary coder and coded all the data. A second coder who was blind to 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 ρ = 0.98).

Timing

Studies 1ab: Human data were obtained from a Google Scholar search performed during April 2021, using the exact query: "social dominance matrix children".
Studies S1ab, 2, 3, 4: Start date: March 2017; end date : June 2018.
Studies 5ab,6ab,7ab: Start date: February 2017; end date: March 2022 (no data collection in 2020-2021)

Data exclusions

Studies 1ab: 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 datasets). When repeated measurements were reported for the same group of animals, we kept only the first reported measure in the analysis (48 groups).

Studies S1ab, 2, 3, 4: One participant was excluded from analysis for cheating (i.e., drawing the relations on a sheet of paper).

Studies 5ab,6ab,7ab: Infants 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), and technical failure (1).
Non-participation	No participant dropped out except for the 11 infants who cried or left their parent's lap before the end of the experiment (see data exclusions above)
Randomization	Participants were allocated randomly to experimental groups

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging