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# Characterization of hunter-gatherer networks and implications for cumulative culture

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**Social networks in modern societies are highly structured, usually involving frequent contact with a small number of unrelated 'friends'[1]. However, contact network structures in traditional small-scale societies, especially hunter-gatherers, are poorly characterized. We developed a portable wireless sensing technology (motes) to study within-camp proximity networks among Agta and BaYaka hunter-gatherers in fine detail. We show that hunter-gatherer social networks exhibit signs of increased efficiency[2] for potential information exchange. Increased network efficiency is achieved through investment in a few strong links among non-kin 'friends' connecting unrelated families. We show that interactions with non-kin appear in childhood, creating opportunities for collaboration and cultural exchange beyond family at early ages. We also show that strong friendships are more important than family ties in predicting levels of shared knowledge among individuals. We hypothesize that efficient transmission of cumulative culture[3–6] may have shaped human social networks and contributed to our tendency to extend networks beyond kin and form strong non-kin ties.**

We studied in-camp proximity networks (within and between households) as a proxy for social interactions in two hunter-gatherer populations from Africa and southeast Asia. We developed a portable wireless sensing technology (motes; Fig. 1) to record all dyadic interactions within a radius of approximately 3 metres at 2-minute intervals for 15 hours a day (05:00–20:00) over a week, in six Agta camps in the Philippines (200 individuals, 7,210 recorded dyadic interactions) and three BaYaka camps in Congo-Brazzaville (132 individuals, 3,397 dyadic interactions; see Supplementary Table 1 with descriptive statistics for all camp networks). We built high-resolution proximity networks mapping the totality of close-range interactions within each camp. In hunter-gatherers (who lack technology-aided communication), close proximity is an indicator of joint activities such as foraging[7], parental care[8] and information exchange[4].

To investigate a possible relationship between social structure and cultural exchange, we estimated the 'global network efficiency'[2] of our proximity networks. This is a measure of how the properties of a network can aid information flow amongst its individuals (nodes) irrespective of whether exchange of information actually occurs, and is therefore a structural property independent from the nature of the information flow. For example, when planning a new town, engineers may want to compare alternative configurations of road systems and select the one that minimizes average distance or travelling time between any two points, irrespective of mode of transport. Global network efficiency provides a measure of ease of transmission across a network, and has been applied to studies of social networks as well as power grids, phone networks, neural systems and transportation networks[2], among others.

To estimate global network efficiency, we first built weighted social networks using our motes proximity data from Agta and BaYaka camps (Fig. 2a and Supplementary Fig. 1), and subdivided the networks into three decreasing levels of relatedness: close kin (parents, children, siblings, partners), extended family (grandparents, grandchildren, aunts, uncles, nieces, nephews, first cousins, parents-in-law, siblings-in-law) and non-kin (see Methods for details of kin categorization, and Supplementary Tables 2 and 3 for percentages of links for each kin category and age groups). We estimated the contribution of each relatedness level to global network efficiency by comparing our hunter-gatherer network structures with randomly permuted networks (the baseline for estimation of efficiencies of real networks). Our randomization procedure does not modify the total number of links (edges), sum of all link weights (number of recorded interactions for each dyad) or degree (number of links) of each node, but randomly shuffles links among nodes within each level of relatedness. For example, when randomizing the non-kin network, we preserve the number of non-kin links from each individual (number of friends) but redistribute their target nodes (identity of their friends). Since our networks are weighted (as each dyad may have been in close proximity multiple times during the one-week interval), random reshuffling of links also changes the strength of friendships. For each of the three categories of relatedness, we created an ensemble of 1,000 randomized graphs (see Methods for procedures). The average global efficiency of the randomized ensemble was then compared with the global efficiency of the corresponding observed networks for each camp.

Our analyses show that randomization of interactions among either close kin or extended family (including affinal kin) does not affect the global efficiency of hunter-gatherer networks. In contrast, randomization of non-kin relationships (friends) greatly reduces global network efficiency (Fig. 2b, and Supplementary Fig. 2 for other camps) both in the Congo-Brazzaville and the Philippines camps (Fig. 2c). The reason is that randomization of non-kin links homogenizes their weights, eliminating strong friendships from networks. This is not observed in the case of randomization of close kin and distant kin links, which do not exhibit the same levels of the heterogeneity in strength of links. Therefore, increased global efficiency in our networks results from investing in a few strong 'close

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Stage B: redistributing weights to the new adjacency matrix.

5. Each node $i$ has a total number of beacons equal to its strength $s_i$ (the sum of the weights of all its links). Each of these beacons is randomly reallocated with uniform probability to one of the $k_i$ new neighbours.

Steps (1–5) are repeated for each node and for each of its links.

Next, we considered the network with close kin and extended family links, and then randomized only extended family links according to the procedure above. Finally, we considered the network with close kin, extended family and non-kin links, and randomized only non-kin links. For each of the three cases, we used $M = 100$ iterations, and we created an ensemble of 1,000 randomized graphs. The average global efficiency obtained for the ensemble of randomized graphs was compared with the global efficiency of the real networks at the three relatedness levels for each camp. We also performed randomizations preserving household structure, where for each level of dyadic relatedness (close kin, extended family and non-kin) we checked whether the original dyad was within or between households, and only allowed randomization to occur respectively within or between households. Results remained mostly unchanged (Supplementary Fig. 3).

*Network transitivity.* Since our networks are weighted, we measured transitivity (a measure of local efficiency) as the total strength of the triads found in our network. To do this, we calculated the third power of the weighted adjacency matrix. The element $i,j$ of the resulting matrix $\mathbf{A}^3$ measures the strength of the walks of length 3 starting from node $i$ and reaching node $j$. In this way, the $i$th element of the diagonal of matrix $\mathbf{A}^3$ gives the total strength of a closed triad starting and ending at node $i$. Summing all the elements of the diagonal (that is, computing the trace of $\mathbf{A}^3$) and dividing by 6, since each triad is counted twice (once in each direction) for each of its three nodes, we obtain the total strength of the triads, the transitivity of the weighted network:

$$T = \frac{1}{6}\sum_{i=1} A_{ii}^3$$

As in the case of global efficiency, the values of network transitivity of the hunter-gatherer real networks were compared with the averages obtained for randomized ensembles.

**Data availability.** The data that support the findings of this study are available from A.B.M. upon request.

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## Author contributions

A.B.M. conceived the project, S.V. designed the motes, A.B.M., M.D., J.T., A.E.P., D.S., G.D.S., N.C. and S.V. collected data, G.D.S. provided video images from Congo and collected data on plant knowledge, J.G.-G. and V.L. performed social network analysis, J.G.-G., S.V., A.E.P., M.D., D.S., N.C., J.S., J.T., V.L., L.V and A.B.M. analysed the data, R.M. commented on the manuscript, and A.B.M., L.V., M.G.T. and V.L. wrote the paper with help from all other authors.

## Additional information

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## Competing interests

The authors declare no competing interests.