Supplementary Materials

Dynamic network partnerships and social contagion drive cooperation

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MATERIAL AND METHODS

Proximity Data-Logging

Given that wire-tailed manakin social interactions take place in fixed locations (i.e., stable territories), individual variation in social behavior and population social structure can be observed by tracking male-male interactions at territories within each lek. Territorial and floater males were outfitted with coded nano-tags (NTQB-2, Lotek Wireless; 0.35g or ~3% of male body mass). These nano-tags transmit over a single VHF frequency (165 MHz), with each tag transmitting a unique digital ID. Tags were programmed with a 20 second pulse rate and a 12 hour on-off duty cycle for continuous monitoring over ~90 days. To measure manakin behavior, we used proximity data-loggers (hereafter DL; SRX-DL800, Lotek Wireless) with short whip antennas in the male territories. DLs were set with a gain range of 60 to 70 dB to constrain detections within each territory (~30 m radius, Fig. 2). Although the vast majority (> 95%) of receivers had gain set at 65 dB, the spatial proximity and/or vegetation density of certain territories occasionally required gain reduction (60 dB) or gain increase (70 dB) to maintain consistent detection radii. The resulting data stream recorded the ID of each unique tag detection, its date and time stamp, and a measure of the received signal strength in log decibel (dB) units (hereafter RSSI).

Behavioral Rule Set

Automated data-logging approaches can greatly increase the quantity and quality of data available to construct social networks and characterize behavior; however, these automated approaches require prior natural history knowledge of a particular system or behavior (Ryder *et al.* 2012). As such, we based our methods on previous studies of wire-tailed manakins showing that spatial co-occurrence within a territory is a both a necessary prerequisite for, and an accurate predictor of, long-term cooperative partnerships among males (Ryder *et al.* 2008, 2009, 2011, 2012). Thus, we defined a social interaction as two tags that were detected sequentially within 45 seconds of one another with a difference in RSSI values (Δ RSSI) < 10, indicating close spatial proximity (Fig. 2). This temporal threshold (< 45 s) was chosen to allow for the fact that each tag pings with a 20 second pulse rate, such that overlapping individuals could potentially have a 40 s gap between their respective pings. The spatial threshold was chosen to include only the pairs that were closest to each other within the detection radius. For a given male-male dyad, a second co-occurrence in the same location within 5 minutes was considered to be part of the same social interaction, but after a gap of $\geq$ 5 minutes, it was considered to be a new interaction between those two males.

Although this system was designed to minimize the detection radius, there were cases when DLs in adjacent territories had temporally overlapping detections of the same dyad. These overlapping detections could indicate a pair of birds that moved between two spatial locations, or they could indicate a pair that was located between two nearby DLs (e.g., in a position where the two birds could be detected by more than one DL at the same time). We consequently filtered the raw social interaction data (n = 40,127) using the following procedure. First, we ordered the interaction data chronologically by start times, and identified any interactions involving the same dyad that had temporal overlap based on their start and end times. We then calculated an adjusted duration for each interaction by subtracting its overlapping time(s). The first interaction that failed to meet the criterion of having at least 45 seconds of non-overlapping duration was then removed from the data. We repeated this procedure iteratively, until only interactions with a non-overlapping duration of at least 45 seconds remained. In total, this left 36,885 distinct social interactions for further analysis.

Partner Dynamics

A prerequisite for testing indirect effects is that partnerships vary within focal individuals (Fig. 2f). Thus, we computed two descriptive statistics that capture (i) the daily turnover in partner identities, and (ii) the change in relative partner edge weights, respectively, in the manakin system. For our first statistic (partner identity turnover), we first calculated a measure of partner consistency, and then took the inverse of consistency as our measure of turnover. The steps for this calculation were as follows: for each focal bird in our analysis, we first calculated the proportion of days on which he interacted with each unique partner (considering only the top four partners per day, given this cut-off in our statistical analysis). We call this metric *C* for consistency and it can take values from $\frac{1}{d}$ to 1, where *d* is the number of days the focal bird had interactions. Then, we calculated an average *C* per day for the focal bird, took the grand mean, and normalized it on a scale from 0 to 1:

$$C_{focal} = \frac{\left(C_{avg} - \frac{1}{d}\right)}{\left(1 - \frac{1}{d}\right)}$$

Hence, C_{focal} captures how consistently a focal bird interacted with particular partners on a day-to-day basis. We took the inverse $(1 - C_{\text{focal}})$*100% as our measure of partner turnover. Thus, a turnover score of 0% represents complete consistency (no change whatsoever in a male's major partners), whereas a score of 100% represents complete turnover (a male has maximal partnership dynamics). Using this method, we determined that the manakins in our dataset exhibit considerable day-to-day turnover in the identities of their partners (mean = 53% ± SE 2%, n = 135 focal males with >1 day in the analysis).

Given that our variance-partitioning analysis accounts for partner weights, we also computed a second statistic to describe weight dynamics. To do this, we first expressed the top four partnerships per day as percentage weights within focal individuals (i.e., normalized within each focal bird). Then, for each focal bird, we computed the interval max% – min% for each of his partners. The average of this value captures the magnitude of his partner weight dynamics. We found that the manakins also exhibited substantial day-to-day variation in relative partner weights (mean = 45% ± SE 2%).

Ground-Truthing Experiment

To verify the spatial threshold for defining social interactions in our study system, we performed a ground-truthing experiment. Paired tags were moved sequentially along four 30 m-long transects centered on a receiver. The tags were briefly held stationary at 5 m intervals (0 m, 5 m, 10 m… 25 m, in each direction; n = 2,196 measurements total). Although RSSI values decay with distance, the resulting data shown in Fig. 2 illustrate how other factors such as topographic relief, vegetation density and variation in tag signal strength (±3 dB) can contribute to intra- and inter-tag variation in RSSI. To validate our social interaction thresholds, we used these data to reconstruct all possible Δ RSSI values for two tags along the same transect with a known inter-tag distance (n = 1,216,897 pairs). The results are shown in Fig. 2c. When Δ RSSI was < 10, the tags were frequently in close spatial proximity (median inter-tag distance = 5 m), a distance at which two manakins in a display territory would be in visual and acoustic contact. In contrast, when Δ RSSI was ≥ 10, the tags tended to be much further apart (median distance = 15 m; distance > 5 m about 77% of the time). Together, these results confirm that our interaction data are conservative and include pairs that were most likely in close proximity. Previous studies have demonstrated that these physically close interactions are predictive of cooperative partnerships in this system (Ryder *et al.* 2008, 2009).

Behavioral Correlations

To describe correlations among the behavioral phenotypes, we fit a multivariate Gaussian model in MCMCglmm (Hadfield 2017) with the four behavioral phenotypes as dependent variables. To account for other sources of variation, this model included the same syntax described in Box 1 of the main text, except that partner identities were omitted. The key feature of this multivariate model was that it also included an unstructured covariance matrix for Focal.ID in the random effects and another unstructured covariance matrix for the residual (within-individual) variation (Houslay & Wilson 2017); this allowed us to compute the correlations among phenotypes while accounting for other sources of variation. We used the posterior variance and covariance estimates for each pair of phenotypes to calculate correlation coefficients, as follows:

$$Corr(PhenotypeA, PhenotypeB) = \frac{Cov(PhenotypeA, PhenotypeB)}{\sqrt{Var_{PhentoypeA} \times Var_{PhenotypeB}}}$$

This model was run with a burn-in of 3,000, storing every 100th sample for a total of 2,000 stored samples. The posterior correlation coefficients are shown in Table S2.

References

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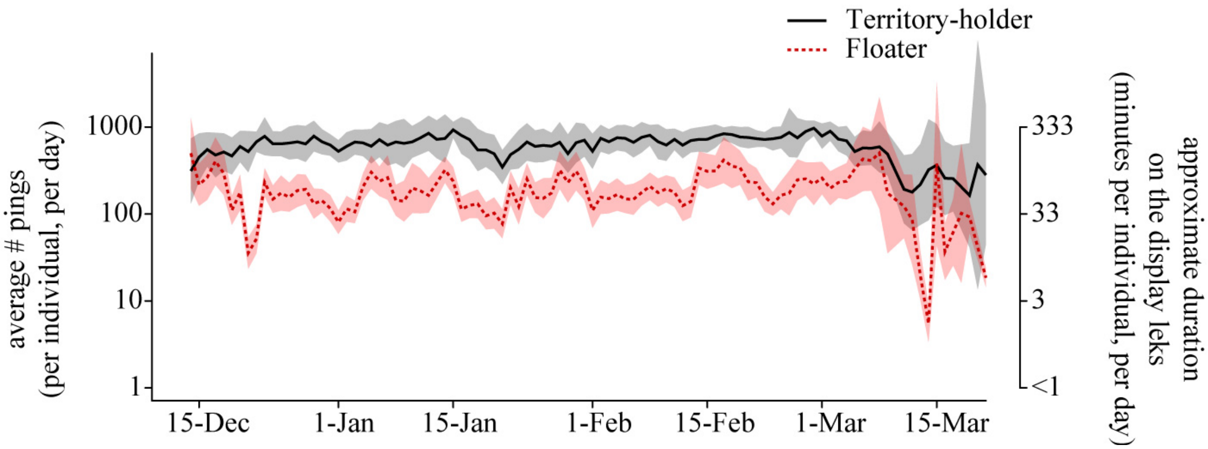

Fig. S1. Seasonal variation in effort (attendance) on the lek territories. Territorial males have attendance rates approximately 3- to 5-fold greater than floater males. The graph shows daily average effort ±SE, with the daily average calculated across individuals and study years. Note that the y-axis is a log scale. Given that the tags pulse every 20 seconds, 100 pings represent approximately 33 minutes of attendance.

Table S1. Descriptive statistics (grand mean ± SE) for n = 144 focal individuals in the MMM analysis (i.e., unmanipulated individuals with partnerships known on the previous day). Population means are calculated using the mean of individual means.

Phenotype	Year 1 (15-16)		Year 2 (16-17)		Year 3 (17-18)	
	Territorial n = 46	Floater n = 32	Territorial n = 41	Floater n = 48	Territorial n = 35	Floater n = 32
Effort (pings /day)	575 ± 59	101 ± 37	948 ± 59	321 ± 53	756 ± 61	149 ± 27
Strength (interactions /day)	8.2 ± 0.8	6.5 ± 1.0	26.2 ± 2.8	28.3 ± 5.0	8.3 ± 0.9	6.9 ± 0.8
Degree (partners /day)	2.6 ± 0.1	3.1 ± 0.3	4.5 ± 0.3	5.3 ± 0.4	2.3 ± 0.1	2.4 ± 0.2
Importance (proportion)	0.49 ± 0.03	0.35 ± 0.05	0.36 ± 0.03	0.22 ± 0.02	0.52 ± 0.03	0.49 ± 0.04

Table S2. Posterior estimates for the behavioral correlations among- and within-individuals. Correlation coefficients are on a scale from –1 to +1. Each cell gives the median posterior pairwise correlation estimate followed by the [95% central range] (n = 2,395 observations of 144 focal individuals used in the MMM analysis). This analysis follows the main variance-partitioning analysis by accounting for status, study year, date, and lek.

Among-individuals

	Effort	Strength	Degree	Importance
Effort	--	0.66 *[0.52, 0.76]*	0.46 *[0.27, 0.60]*	0.18 *[–0.02, 0.37]*
Strength		--	0.88 *[0.81, 0.92]*	–0.12 *[–0.30, 0.09]*
Degree			--	–0.44 *[–0.59, –0.25]*
Importance				--

Within-individuals

	Effort	Strength	Degree	Importance
Effort	--	0.47 *[0.44, 0.50]*	0.30 *[0.27, 0.33]*	0.15 *[0.11, 0.19]*
Strength		--	0.71 *[0.70, 0.73]*	0.10 *[0.06, 0.13]*
Degree			--	–0.22 *[–0.26, –0.18]*
Importance				--

Table S3. Results of the weighted MMM analysis of direct and indirect effects in manakin social networks. The fixed effects are estimated as the change in the response variable (phenotype) across status classes and study years, respectively. For the random effects, the statistic is the proportion of total phenotypic variance (SD^2) explained on a scale from 0 to 1. R^2_{Bayes} is a measure of the variance explained by the whole model on a scale from 0 to 1.

Phenotype		Statistic	Posterior median	95% Central range (lower, upper)	Comparison to null (p-value)
Effort	Fixed effects	Status (terr vs floa)	0.86	0.70, 1.01	
R^2_{Bayes} = 0.53		Study year (2 vs 1)	0.47	0.35, 0.59	
		Study year (3 vs 1)	0.39	0.25, 0.52	
	Random effects	Direct effect	0.30	0.22, 0.38	0.003
		Indirect effect	0.12	0.07, 0.18	0.003
		Date	0.03	0.02, 0.05	
		Lek	0.09	0.03, 0.27	
		Residual	0.44	0.35, 0.52	
Strength	Fixed effects	Status (terr vs floa)	0.31	0.17, 0.46	
R^2_{Bayes} = 0.53		Study year (2 vs 1)	0.78	0.65, 0.91	
		Study year (3 vs 1)	0.07	–0.08, 0.22	
	Random effects	Direct effect	0.24	0.18, 0.32	0.002
		Indirect effect	0.19	0.13, 0.26	0.002
		Date	0.05	0.03, 0.08	
		Lek	0.08	0.03, 0.24	
		Residual	0.41	0.33, 0.48	
Degree	Fixed effects	Status (terr vs floa)	0.01	–0.11, 0.14	
R^2_{Bayes} = 0.52		Study year (2 vs 1)	0.62	0.47, 0.76	
		Study year (3 vs 1)	–0.20	–0.36, –0.04	
	Random effects	Direct effect	0.12	0.08, 0.18	0.001
		Indirect effect	0.21	0.13, 0.29	0.004
		Date	0.08	0.05, 0.11	
		Lek	0.12	0.04, 0.33	
		Residual	0.46	0.34, 0.53	
Importance	Fixed effects	Status (terr vs floa)	0.31	0.17, 0.45	
R^2_{Bayes} = 0.49		Study year (2 vs 1)	–0.36	–0.49, –0.23	
		Study year (3 vs 1)	0.38	0.23, 0.52	
	Random effects	Direct effect	0.17	0.12, 0.24	0.003
		Indirect effect	0.24	0.16, 0.33	0.005
		Date	0.03	0.02, 0.05	
		Lek	0.08	0.01, 0.26	
		Residual	0.45	0.36, 0.53	