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Intermittent collective motion in sheep results from alternating the role of leader and follower

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Supplementary Information
Intermittent collective motion in sheep: temporal leaders and information flow

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SUPPLEMENTARY NOTE S1: EXPERIMENTAL SETUP

The experiments were performed at the experimental farm of Domaine du Merle (43.64°N and 5.01°E), within the Crau region in the south of France. Experiments were performed with Merino Arles sheep (*Ovis aries* Linnaeus) of the same age (18-month-old) and sex (females). The experimental setup consisted of four adjacent 80×80 m arenas, delimited by sheep fences. Each arena was a flat, homogeneous irrigated native pasture of the Crau region. A green polypropylene (1.2-meter-high) net was used to visually isolate sheep from the immediate surroundings and from other arenas. A 7-meter-high tower placed in the center of the setup was used to register the position of the individuals, as can be seen in the scheme in Extended Data Fig. 1. On each day of the experiment, groups of size N of randomly selected, unrelated individuals were allocated in a visually isolated arena. We studied groups of size $N = 2$, 3, and 4. We used a digital camera (Canon EOS D50) to record the activity of the individuals in the arena for periods of 30 minutes (≈ 2000 seconds). The camera was anchored at the top of the tower and was connected to a PowerBook laptop. Snapshots were taken by the camera every second. The data acquisition (i.e. video recording) began 30 minutes after the animals were introduced in the arena. All group size experiments were replicated several times. For all group sizes ($N = 2, 3$ and 4) we performed 8 different replications. Animal care and experimental manipulations were applied in conformity with the rules of the Ethics Committee for Animal Experimentation of Federation of Research in Biology of Toulouse.

Data collection

No automatic tracking of the individuals was used to extract the information from the video recording due to following difficulties. The contrast between individuals and background contained high fluctuations and the recording angle of the camcorder with respect to the arena made possible that individuals could hide each other from the camera viewpoint. To overcome these difficulties, we used manual tracking on a Cintiq interactive pen display Cintiq 21 UX (UXGA 1,600 × 1,200 pixels) using dedicated software written by J. Gautrais [1]. The software uses projective geometry to obtain the positions $\boldsymbol{x}_i(t)$ for each sheep inside the arena from the positions in the video snapshots. The instantaneous velocity $\boldsymbol{v}_i(t) = (\boldsymbol{x}_i(t + \Delta t) - \boldsymbol{x}_i(t))/\Delta t$ of each sheep was obtained by using their positions in two consecutive images. All this information was obtained for each second for all group sizes.

SUPPLEMENTARY NOTE S2: CHARACTERIZATION OF COLLECTIVE MOTION PHASES

Group size $N = 2$	**Group size** $N = 3$	**Group size** $N = 4$
$v_{th} = 0.464$ m/s	$v_{th} = 0.445$ m/s	$v_{th} = 0.442$ m/s

Table TS1: The threshold speeds for all group sizes $N = 2, 3, 4$.

Group size $N = 2$	**Group size** $N = 3$	**Group size** $N = 4$
$v_0 = (0.87 \pm 0.16)$ m/s	$v_0 = (0.86 \pm 0.12)$ m/s	$v_0 = (0.89 \pm 0.11)$ m/s

Table TS2: The average individual speeds for all group sizes $N = 2, 3, 4$ during the Collective Motion phases (CMPs).

SUPPLEMENTARY NOTE S3: DECIPHERING THE INTERACTION NETWORK AND THE NAVIGATION MECHANISM DURING THE CMPS

We estimate the influence of an individual i on an individual j in the group during a CMP in the experiments by computing the velocity crosscorrelation $C_{ij}^{\mathrm{exp}}(\tau)$, defined for a given CMP of duration $T_{\mathrm{CMP}} = T_{\mathrm{end}} - T_{\mathrm{ini}}$ as:

$$C_{ij}^{\mathrm{exp}}(\tau) = \frac{1}{T_{\mathrm{CMP}}} \int_{T_{\mathrm{ini}}}^{T_{\mathrm{end}}} \mathbf{v}_i(t) \cdot \mathbf{v}_j(t+\tau)\, dt, \tag{S1}$$

where $\mathbf{v}_i(t)$ is the velocity of individual i at time t. As shown in Fig. 3**a** in the main text, $C_{ij}^{\mathrm{exp}}(\tau) \neq C_{ij}^{\mathrm{exp}}(\tau)$, which indicates that interactions between individuals during CMPs are non-reciprocal. We stress that observing non-reciprocal interactions between individual i and j does not imply a priori that either the interaction of i over j or j over i can be neglected, as suggested in [2]. Both interactions can be present. However, we can ensure that they are not identical in magnitude, but with opposite sign, as occurs when Newton's third law applies. Thus, we assume a generic scenario where all interactions are possible. Furthermore, we consider, as explained in the main text, that individual i navigates using as input: i) the velocity of the neighbors, i.e. a velocity alignment mechanism (model V), ii) the position of the neighbors (model P), and iii) the velocity and position of the neighbors (model V+P). Knowing that individuals move with constant speed v_0 during the CMPs, the equations of motion are given by:

$$\dot{\mathbf{x}}_i(t) \;=\; v_0\, \widehat{\mathbf{e}}\big(\theta_i\big)\,, \tag{S2}$$

for the update of the position in model V, P, and V+P, while the temporal evolution of the angle θ_i is given by:

$$\dot{\theta}_i(t) \;=\; \sum_{j=1}^{N} \tilde{A}_{K[i]K[j]} \sin\Big(\theta_j(t) - \theta_i(t)\Big) + \sqrt{2\,D_\theta}\;\xi_i(t)\ \text{[for model V]} \tag{S3}$$

$$\dot{\theta}_i(t) \;=\; \sum_{j=1}^{N} \tilde{A}_{K[i]K[j]} \sin\Big(\alpha_{ij}(t) - \theta_i(t)\Big) + \sqrt{2\,D_\theta}\;\xi_i(t)\ \text{[for model P]} \tag{S4}$$

$$\dot{\theta}_i(t) \;=\; \sum_{j=1}^{N} \tilde{A}^{\mathrm{V}}_{K[i]K[j]} \sin\Big(\theta_j(t) - \theta_i(t)\Big) + \sum_{j=1}^{N} \tilde{A}^{\mathrm{P}}_{K[i]K[j]} \sin\Big(\alpha_{ij}(t) - \theta_i(t)\Big) + \sqrt{2\,D_\theta}\;\xi_i(t)\ \text{[for model V+P]}\,, \tag{S5}$$

where $\tilde{A}_{K[i]K[j]}$, $\tilde{A}^{\mathrm{V}}_{K[i]K[j]}$, $\tilde{A}^{\mathrm{P}}_{K[i]K[j]}$, and D_θ are constants to be determined, $\xi_i(t)$ is a white noise that satisfies the condition $\langle \xi_i(t) \cdot \xi_j(t') \rangle = \delta_{i,j}\delta(t-t')$, and $\alpha_{ij}(t)$ is defined in the main text. The notation of $\tilde{A}_{K[i]K[j]}$, $\tilde{A}^{\mathrm{V}}_{K[i]K[j]}$, $\tilde{A}^{\mathrm{P}}_{K[i]K[j]}$ used in equations (S3), (S4) and (S5) is the same as the one introduced in the Methods section in equations (5), (6) and (7), where $K[i]$ is the rank of individual i during the CMP. If we keep this ranking-based notation, then the correlation of equation (S1) can be rewritten as:

$$C_{K[i]K[j]}^{\mathrm{exp}}(\tau) = \frac{1}{T_{\mathrm{CMP}}} \int_{T_{\mathrm{ini}}}^{T_{\mathrm{end}}} \mathbf{v}_i(t) \cdot \mathbf{v}_j(t+\tau)\, dt. \tag{S6}$$

Since we have non-reciprocal interactions, we can anticipate that $\tilde{A}_{K[i]K[j]} \neq \tilde{A}_{K[j]K[i]}$ (it similarly happens to $\tilde{A}^{\mathrm{V}}_{K[i]K[j]}$ and $\tilde{A}^{\mathrm{P}}_{K[i]K[j]}$). The most generic model is the one that contains all possible interactions – whose associated interaction network is referred to as IN1 in the main text, see Fig. 3**b** – and considers a navigation mechanism that operates with the velocity and position of the neighbors, i.e. model V+P. While this is certainly the most generic model, it is also the model with the largest number of parameters by far. If we use a generic model with a large number of parameters like this one, we incur a risk of overfitting, in the sense that several elements of the model do not help to significantly improve the fitting of the data. Models V and P, as well as the simplified interaction networks IN2 and IN3 (see Fig. 3**b**), are introduced to investigate the role played by each element in the model and to identify the minimal requirements – i.e. the model with the smallest number of parameters – consistent with the experimental data.

With this purpose in mind, we perform a large number of simulations for each navigation mechanism (model V, P, and V+P), interaction network (IN1, IN2, and IN3), and group size ($N = 2$, 3, and 4) – which define a set of parameters

$\mathbf{a} = \{\tilde{A}_{K[i]K[j]}, D_\theta\}$ – using as initial conditions those in the experimental CMPs. We then compute for each set of parameters $\mathbf{a}$ the velocity crosscorrelation $C^{\text{model}}_{K[i]K[j]}(\tau)$ and calculate the mean value $\langle C^{\text{model}}_{K[i]K[j]}(\tau)\rangle$ and variance $\sigma_{K[i]K[j]}$ of this quantity. We then estimate its distribution as $P(C^{\text{model}}_{K[i]K[j]}(\tau;\mathbf{a})) \propto \exp\left(-\frac{(C^{\text{model}}_{K[i]K[j]}(\tau)-\langle C^{\text{model}}_{K[i]K[j]}(\tau)\rangle)^2}{2\,\sigma^2_{K[i]K[j]}}\right)$ and build the likelihood function $\mathtt{L}(\tau;\mathbf{a}) \propto \prod_{\text{k}} \prod_{K[i],K[j]} \exp\left(-\frac{(C^{\text{k}}_{K[i]K[j]}(\tau)-C^{\text{model}}_{K[i]K[j]}(\tau))^2}{2\sigma^2_{K[i]K[j]}}\right)$, where $C^{\text{k}}_{K[i]K[j]}$ refers to the value computed in the k-th experimental CMP. Finding the set of parameters $\mathbf{a}$ that maximizes the likelihood function is then reduced to find the minimum of the function $\mathcal{F}(\mathbf{a}) = \int_0^\infty d\tau \sum_{\text{k}} \sum_{K[i],K[j]} (C^{\text{k}}_{K[i]K[j]}(\tau) - C^{\text{model}}_{K[i]K[j]}(\tau,\mathbf{a}))^2/\sigma_{K[i]K[j]}$. We compute this minimum of $\mathcal{F}(\mathbf{a})$ by using the Steepest Descent Method (SDM) [3]. The procedure is applied to IN1, IN2, and IN3 using the navigation models V, P, and V+P. The obtained optimal values of the parameters $\mathbf{a}$, as well as the maximum likelihood $\mathtt{L}^*$ for the optimal $\mathbf{a}$, are presented in the following tables:

model P, $N=2$			
IN 1			
$\tilde{A}^P_{21}=2.7128$	$\tilde{A}^P_{12}=0.0008$	$D=0.0070$	$\mathtt{L}^*=0.1184$
IN 2 & IN 3			
$\tilde{A}^P_{21}=2.7260$	$D=0.0107$	$\mathtt{L}^*=0.1085$	

model V, $N=2$			
IN 1			
$\tilde{A}^V_{21}=0.7284$	$\tilde{A}^V_{12}=0.0012$	$D=0.0052$	$\mathtt{L}^*=0.0170$
IN 2 & IN 3			
$\tilde{A}^V_{21}=0.7356$	$D=0.0057$	$\mathtt{L}^*=0.0107$	

model V+P, $N=2$			
IN 1			
$\tilde{A}^P_{21}=2.4338$ $D=0.0120$	$\tilde{A}^P_{12}=0.0092$ $\mathtt{L}^*=0.0014$	$\tilde{A}^V_{21}=0.0775$	$\tilde{A}^V_{12}=0.0017$
IN 2 & IN 3			
$\tilde{A}^P_{21}=2.6047$	$\tilde{A}^V_{21}=0.0741$	$D=0.0054$	$\mathtt{L}^*=0.0026$

model P , $N=3$			
IN 1			
$\tilde{A}^P_{21}=3.2321$ $\tilde{A}^P_{13}=0.0029$	$\tilde{A}^P_{31}=2.1134$ $\tilde{A}^P_{23}=0.3029$	$\tilde{A}^P_{12}=0.0056$ $D=0.0112$	$\tilde{A}^P_{32}=0.3032$ $\mathtt{L}^*=3.7378$
IN 2			
$\tilde{A}^P_{21}=3.4354$ $\mathtt{L}^*=2.4641$	$\tilde{A}^P_{31}=2.5631$	$\tilde{A}^P_{32}=0.3261$	$D=0.0105$
IN 3			
$\tilde{A}^P_{21}=3.3048$	$\tilde{A}^P_{32}=3.0723$	$D=0.0118$	$\mathtt{L}^*=4.07$

model V , $N=3$			
IN 1			
$\tilde{A}^V_{21}=0.7891$ $\tilde{A}^V_{13}=0.0010$	$\tilde{A}^V_{31}=0.5693$ $\tilde{A}^V_{23}=0.0410$	$\tilde{A}^V_{12}=0.0004$ $D=0.0112$	$\tilde{A}^V_{32}=0.0413$ $\mathtt{L}^*=0.6468$
IN 2			
$\tilde{A}^V_{21}=0.7827$ $\mathtt{L}^*=0.7300$	$\tilde{A}^V_{31}=0.5820$	$\tilde{A}^V_{32}=0.0362$	$D=0.0108$
IN 3			
$\tilde{A}^V_{21}=0.9606$	$\tilde{A}^V_{32}=1.5663$	$D=0.0090$	$\mathtt{L}^*=2.0152$

model V+P , $N=3$			
IN 1			
$\tilde{A}^P_{21}=3.5136$	$\tilde{A}^P_{31}=1.7689$	$\tilde{A}^P_{12}=0.0059$	$\tilde{A}^P_{32}=0.4299$
$\tilde{A}^P_{13}=0.0008$	$\tilde{A}^P_{23}=0.2299$	$\tilde{A}^V_{21}=0.2478$	$\tilde{A}^V_{31}=0.3128$
$\tilde{A}^V_{12}=0.0002$	$\tilde{A}^V_{32}=0.0447$	$\tilde{A}^V_{13}=0.0031$	$\tilde{A}^V_{23}=0.0347$
$D=0.0108$	$\mathtt{L}^*=0.4885$		
IN 2			
$\tilde{A}^P_{21}=2.8826$	$\tilde{A}^P_{31}=2.2763$	$\tilde{A}^P_{32}=0.1422$	$\tilde{A}^V_{21}=0.2320$
$\tilde{A}^V_{31}=0.1677$	$\tilde{A}^V_{32}=0.2060$	$D=0.0115$	$\mathtt{L}^*=0.6021$
IN 3			
$\tilde{A}^P_{21}=3.4548$	$\tilde{A}^P_{32}=2.8766$	$\tilde{A}^V_{21}=0.3318$	$\tilde{A}^V_{32}=0.3730$
$D=0.0101$	$\mathtt{L}^*=1.1421$		

model P , $N=4$			
IN 1			
$\tilde{A}^P_{21}=3.2398$	$\tilde{A}^P_{31}=3.3061$	$\tilde{A}^P_{41}=2.4690$	$\tilde{A}^P_{12}=0.0001$
$\tilde{A}^P_{32}=2.2682$	$\tilde{A}^P_{42}=2.3958$	$\tilde{A}^P_{13}=0.0058$	$\tilde{A}^P_{23}=0.1944$
$\tilde{A}^P_{43}=2.1637$	$\tilde{A}^P_{14}=0.0024$	$\tilde{A}^P_{24}=0.9738$	$\tilde{A}^P_{34}=1.4589$
$D=0.0021$	$\mathtt{L}^*=2.0344$		
IN 2			
$\tilde{A}^P_{21}=2.5656$	$\tilde{A}^P_{31}=3.3288$	$\tilde{A}^P_{41}=2.2856$	$\tilde{A}^P_{32}=1.5801$
$\tilde{A}^P_{42}=2.1245$	$\tilde{A}^P_{43}=2.3498$	$D=0.0029$	$\mathtt{L}^*=1.4936$
IN 3			
$\tilde{A}^P_{21}=5.9597$	$\tilde{A}^P_{32}=5.3958$	$\tilde{A}^P_{43}=6.2602$	$D=0.0016$
$\mathtt{L}^*=3.0021$			

model V , $N=4$			
IN 1			
$\tilde{A}^V_{21}=1.0231$	$\tilde{A}^V_{31}=0.5979$	$\tilde{A}^V_{41}=0.5654$	$\tilde{A}^V_{12}=0.0229$
$\tilde{A}^V_{32}=0.0325$	$\tilde{A}^V_{42}=0.0683$	$\tilde{A}^V_{13}=0.0128$	$\tilde{A}^V_{23}=0.0322$
$\tilde{A}^V_{43}=0.0422$	$\tilde{A}^V_{14}=0.0102$	$\tilde{A}^V_{24}=0.0323$	$\tilde{A}^V_{34}=0.0171$
$D=0.0038$	$\mathtt{L}^*=1.956$		
IN 2			
$\tilde{A}^V_{21}=1.1604$	$\tilde{A}^V_{31}=0.5123$	$\tilde{A}^V_{41}=0.4493$	$\tilde{A}^V_{32}=0.0598$
$\tilde{A}^V_{42}=0.0193$	$\tilde{A}^V_{43}=0.0283$	$D=0.0032$	$\mathtt{L}^*=0.754$
IN 3			
$\tilde{A}^V_{21}=1.6730$	$\tilde{A}^V_{32}=0.6761$	$\tilde{A}^V_{43}=0.5373$	$D=0.0023$
$\mathtt{L}^*=0.810$			

model V+P , $N=4$			
IN 1			
$\tilde{A}^P_{21}=3.2134$	$\tilde{A}^P_{31}=2.8783$	$\tilde{A}^P_{41}=2.3455$	$\tilde{A}^P_{12}=0.0018$
$\tilde{A}^P_{32}=2.2260$	$\tilde{A}^P_{42}=3.2192$	$\tilde{A}^P_{13}=0.0058$	$\tilde{A}^P_{23}=0.0342$
$\tilde{A}^P_{43}=1.0383$	$\tilde{A}^P_{14}=0.0022$	$\tilde{A}^P_{24}=0.0114$	$\tilde{A}^P_{34}=0.0020$
$\tilde{A}^V_{21}=0.7140$	$\tilde{A}^V_{31}=0.4105$	$\tilde{A}^V_{41}=0.3035$	$\tilde{A}^V_{12}=0.0628$
$\tilde{A}^V_{32}=0.4171$	$\tilde{A}^V_{42}=0.2953$	$\tilde{A}^V_{13}=0.0040$	$\tilde{A}^V_{23}=0.0377$
$\tilde{A}^V_{43}=0.3626$	$\tilde{A}^V_{14}=0.0118$	$\tilde{A}^V_{24}=0.0296$	$\tilde{A}^V_{34}=0.0500$
$D=0.0035$	$\mathtt{L}^*=0.1803$		
IN 2			
$\tilde{A}^P_{21}=2.9653$	$\tilde{A}^P_{31}=2.2867$	$\tilde{A}^P_{41}=2.3316$	$\tilde{A}^P_{32}=1.1716$
$\tilde{A}^P_{42}=1.5753$	$\tilde{A}^P_{43}=1.1459$	$\tilde{A}^V_{21}=0.7360$	$\tilde{A}^V_{31}=0.4212$
$\tilde{A}^V_{41}=0.4300$	$\tilde{A}^V_{32}=0.4469$	$\tilde{A}^V_{42}=0.3235$	$\tilde{A}^V_{43}=0.4586$
$D=0.0036$	$\mathtt{L}^*=0.3933$		
IN 3			
$\tilde{A}^P_{21}=2.7549$	$\tilde{A}^P_{32}=2.6246$	$\tilde{A}^P_{43}=1.7213$	$\tilde{A}^V_{21}=0.1121$
$\tilde{A}^V_{32}=0.1360$	$\tilde{A}^V_{43}=0.1800$	$D=0.0021$	$\mathtt{L}^*=0.5656$

To select the best model, we use the Akaike Information Criterion (AIC) [4]. The AIC takes into account the number of estimated parameters and the maximum value of the likelihood function. The AIC value is defined as:

$$\mathrm{AIC} = 2q - 2\ln \mathrm{L}^*, \tag{S7}$$

where q is the number of free parameters in the model. Given a set of candidate models for the data, the preferred model is the one with the minimum AIC value. Thus, AIC rewards goodness of fit – as assessed by the likelihood function –, but it also includes a penalty that is an increasing function of the number of estimated parameters, discouraging overfitting. The results of the calculation of the AIC for all models and all group sizes can be found in Table TS3. Note that the interaction networks IN2 and IN3 are exactly the same for groups of size $N = 2$, and thus we provide the same value for both networks. The AIC selects IN3 with navigation model P as the best model for all group sizes.

N = 2			
	IN 1	IN 2	IN 3
model P	AIC = 10.26	AIC = 8.44	
model V	AIC = 14.15	AIC = 13.08	
model V+P	AIC = 23.14	AIC = 17.90	
N = 3			
model P	AIC = 11.36	AIC = 6.19	AIC = 0.72
model V	AIC = 14.87	AIC = 8.63	AIC = 4.60
model V+P	AIC = 27.43	AIC = 15.02	AIC = 9.73
N = 4			
model P	AIC = 24.57	AIC = 13.20	AIC = 5.80
model V	AIC = 24.66	AIC = 14.57	AIC = 8.42
model V+P	AIC = 53.43	AIC = 27.87	AIC = 15.14

Table TS3: Comparison of the AIC results for all interaction networks, navigation models, and group sizes.

SUPPLEMENTARY NOTE S4: STATISTICS ON LEADERSHIP

	Group size $N = 2$	**Group size** $N = 3$	**Group size** $N = 4$
$\sqrt{\mathcal{M}}\, D_{\mathcal{M}}$	0.0600	0.1843	0.1703
$D_{\text{critical},0.05}$	0.1644	0.2873	0.2947

Table TS4: KS statistics for the analysis of leadership presented in the Methods section. Here, $\mathcal{M}$ is the number of experimental data and $D_{\text{critical},0.05}$ is the critical value for a significance value of $\alpha = 0.05$.

	Group size $N = 2$	**Group size** $N = 3$	**Group size** $N = 4$
χ^2	4.60	3.00	2.33
p-value	0.62	0.92	0.73

Table TS5: Quantitative comparison using a χ^2-test for all group sizes.

SUPPLEMENTARY MOVIES

The following videos are provided as supplementary material.

SM.1 .- **Movie_1.avi**: Tracking of a sequence of 4 CMPs extracted from a trial with a group of size $N = 4$, where each individual adopts the leading position one time.

SM.2 .- **Movie_2.mp4**: Alternating Collective Motion Phases (CMPs) and Grazing Phases (GPs) observed in the experiments (raw data) for all group sizes ($N = 2, 3$ and 4).

SM.3 .- **Movie_3.avi**: Tracking of CMPs for group size $N = 4$.

SM.4 .- **Movie_4.mp4**: Numerical simulations of the exploration of the maze shown in Fig. 4**c** in the main text for a group of size $N = 4$ using model P.

SM.5 .- **Movie_5.mp4**: Numerical simulations of the exploration of the maze shown in Fig. 4**c** in the main text for a group of size $N = 4$ using model V.

SM.6 .- **Movie_6.mp4**: Video taken by Richard Bon (Université Paul Sabatier, CRCA, Toulouse, France) of a large group of moving sheep. The video was taken in the Alps.

SM.7 .- **Movie_7.avi**: Numerical simulations implemented for the generalized model using a generalized network IN3 and a group of $N = 40$ individuals. The probability of following a neighbor from the back is $p_0 = 0.8$ (see Methods).

SM.8 .- **Movie_8.mp4**: Numerical simulations implemented using our model (model P + IN3) and a group of $N = 4$ individuals. For aesthetic reasons, we included a more detailed implementation for the transition of the individuals between CMP $\leftrightharpoons$ GP. For the realization of the video, we used a constant time interval between transitions of the individuals in such a way that the leader (rank $K = 1$) makes the transition at a given time $\widehat{t_1}$, then the first follower (rank $K = 2$) makes the transition at time $\widehat{t_2} = \widehat{t_1} + \widehat{d_t}$, the third follower ($K = 3$) makes the transition at time $\widehat{t_3} = \widehat{t_2} + \widehat{d_t}$ and so on. This implementation was used for both transitions: CMP$\rightarrow$GP and GP$\rightarrow$CMP. For the video, we used $\widehat{d_t} = 5$ time units.

SM.9 .- **Movie_9.mp4**: Numerical simulations implemented using a generalization of the model presented in Barberis et al. [5], which is a generic model that considers restricted vision angles of the particles.

[1] F. Ginelli, F. Peruani, M.-H. Pillot, H. Chaté, G. Theraulaz, and R. Bon, "Intermittent collective dynamics emerge from conflicting imperatives in sheep herds," *Proceedings of the National Academy of Sciences*, vol. 112, no. 41, pp. 12729–12734, 2015.

[2] M. Nagy, Z. Ákos, D. Biro, and T. Vicsek, "Hierarchical group dynamics in pigeon flocks," *Nature*, vol. 464, no. 7290, 2010.

[3] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes in C: The Art of Scientific Computing*. Cambridge University Press, 2007.

[4] H. Akaike, "A new look at the statistical model identification," *IEEE Transactions on Automatic Control*, vol. 19, pp. 716–723, December 1974.

[5] L. Barberis and F. Peruani, "Large-scale patterns in a minimal cognitive flocking model: incidental leaders, nematic patterns, and aggregates," *Physical review letters*, vol. 117, no. 24, p. 248001, 2016.