

Vigilance-Based Predator Detection

A probabilistic framework for collective vigilance in mixed-species settings

More watchers help. More independent watchers help more.



Why group vigilance?

Grouping can improve predator detection - but only when added watchers contribute new information.

- Individuals can reduce personal scanning when risk is shared.
- Mixed-species groups may combine different sensory and behavioral cues.
- Synchronization can make those cues redundant.

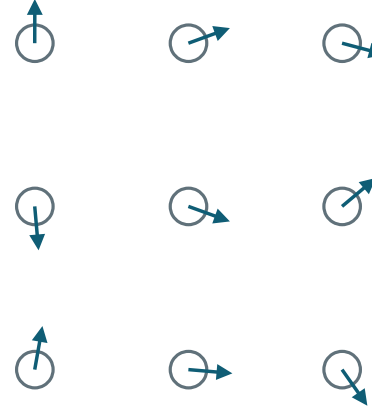
The trade-off

shared
information

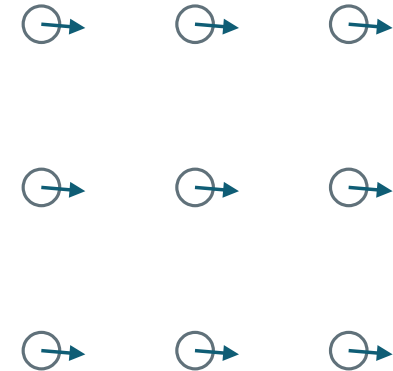


behavioral redundancy

Independent scanning



Synchronized scanning

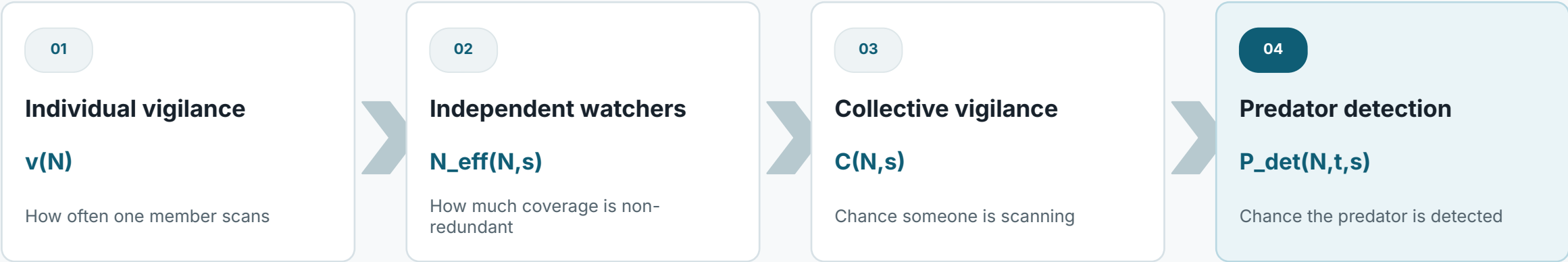


How does group size affect detection?

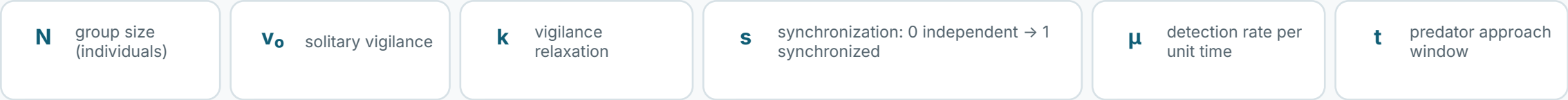
How much does synchronization matter?

When do extra watchers stop adding value?

From individual behavior to detection



Core parameters



Scope: the base model represents a mixed-species advantage through lower behavioral redundancy; species-specific heterogeneity enters in the extension.

Sanity checks: $N = 1 \rightarrow v = v_o$ · $s = 0 \rightarrow N_{\text{eff}} = N$ · $s = 1 \rightarrow N_{\text{eff}} = 1$

Model 1 — Individual vigilance

$$v(N) = \frac{v_0}{1 + k(N - 1)}$$

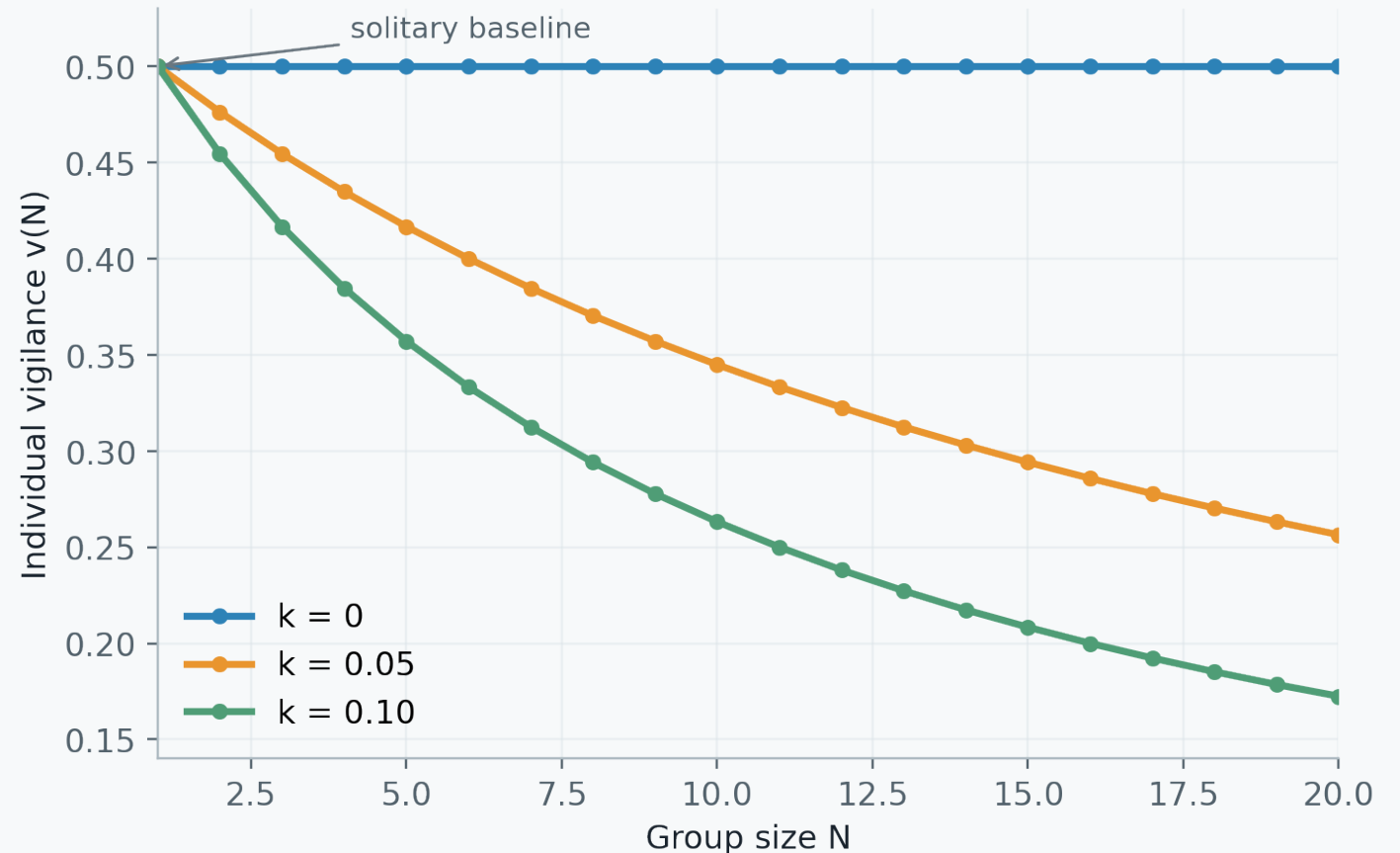
As the group grows, each individual can rely more on others and scan less often.

1 $v(1) = v_0$ by construction

2 Larger N lowers individual vigilance

3 k controls how quickly vigilance relaxes

Mechanism: shared risk ↓ individual scanning.



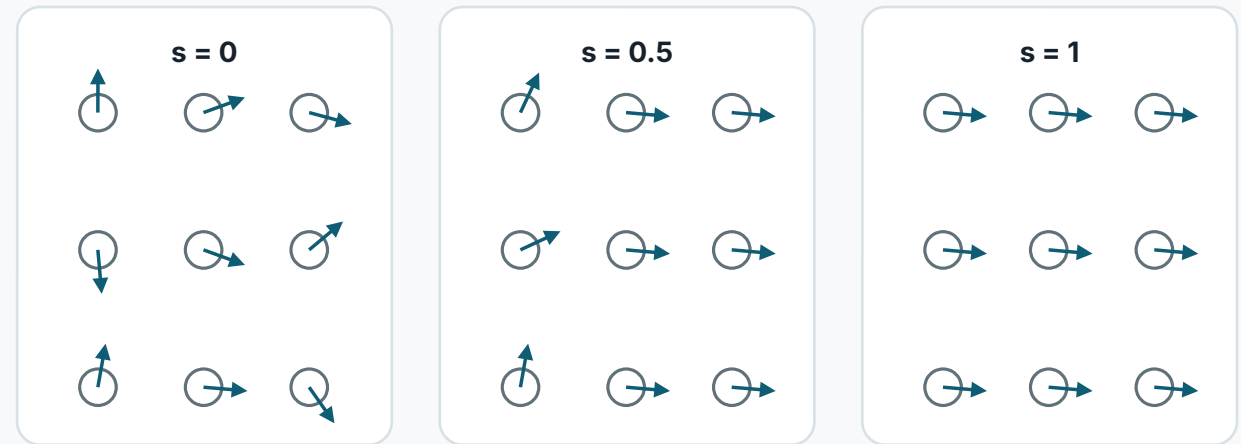
Model 2 — Effective independent watchers

$$N_{\text{eff}}(N, s) = 1 + (N - 1)(1 - s)$$

**Synchronization reduces independent coverage
- not the raw number of animals.**

- $s = 0$: every added member contributes one new independent watcher.
- $s = 1$: the group acts like one effective watcher.
- $0 < s < 1$: only part of each new member's coverage is unique.

This linear form satisfies the required boundary cases and matches the plotted behavior.



more synchronization → more overlapping vigilance → fewer independent watchers

Interpretation

A larger group only helps to the extent that its members contribute non-redundant information.

Model 3 — Collective vigilance

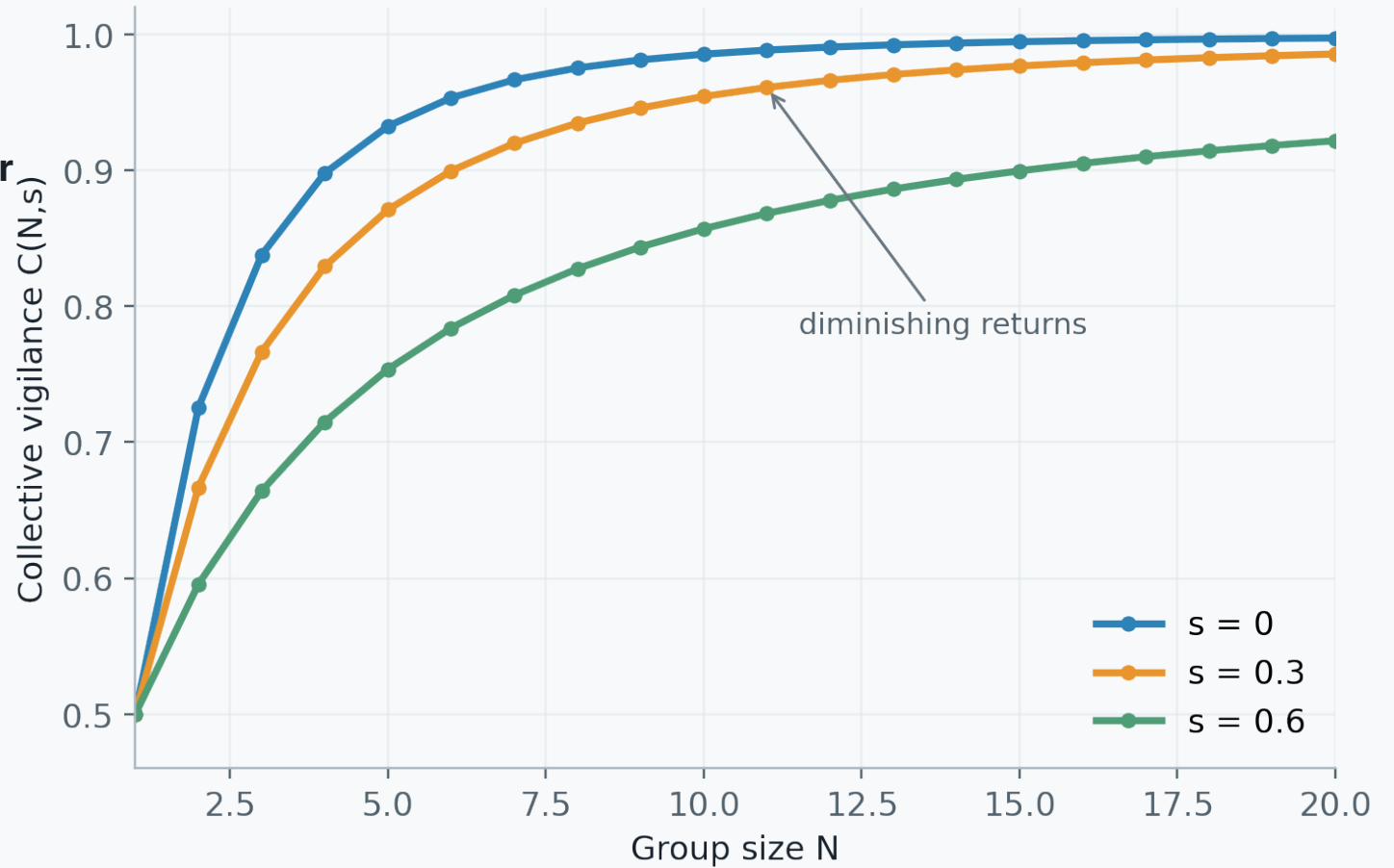
$$C(N, s) = 1 - (1 - v(N))^{N_{\text{eff}}(N, s)}$$

Probability that at least one effective watcher is scanning.

What changes with N?

- Early additions sharply increase the chance that someone is vigilant.
- The curve flattens as coverage becomes increasingly complete.

Higher synchronization slows the gain from adding more members.



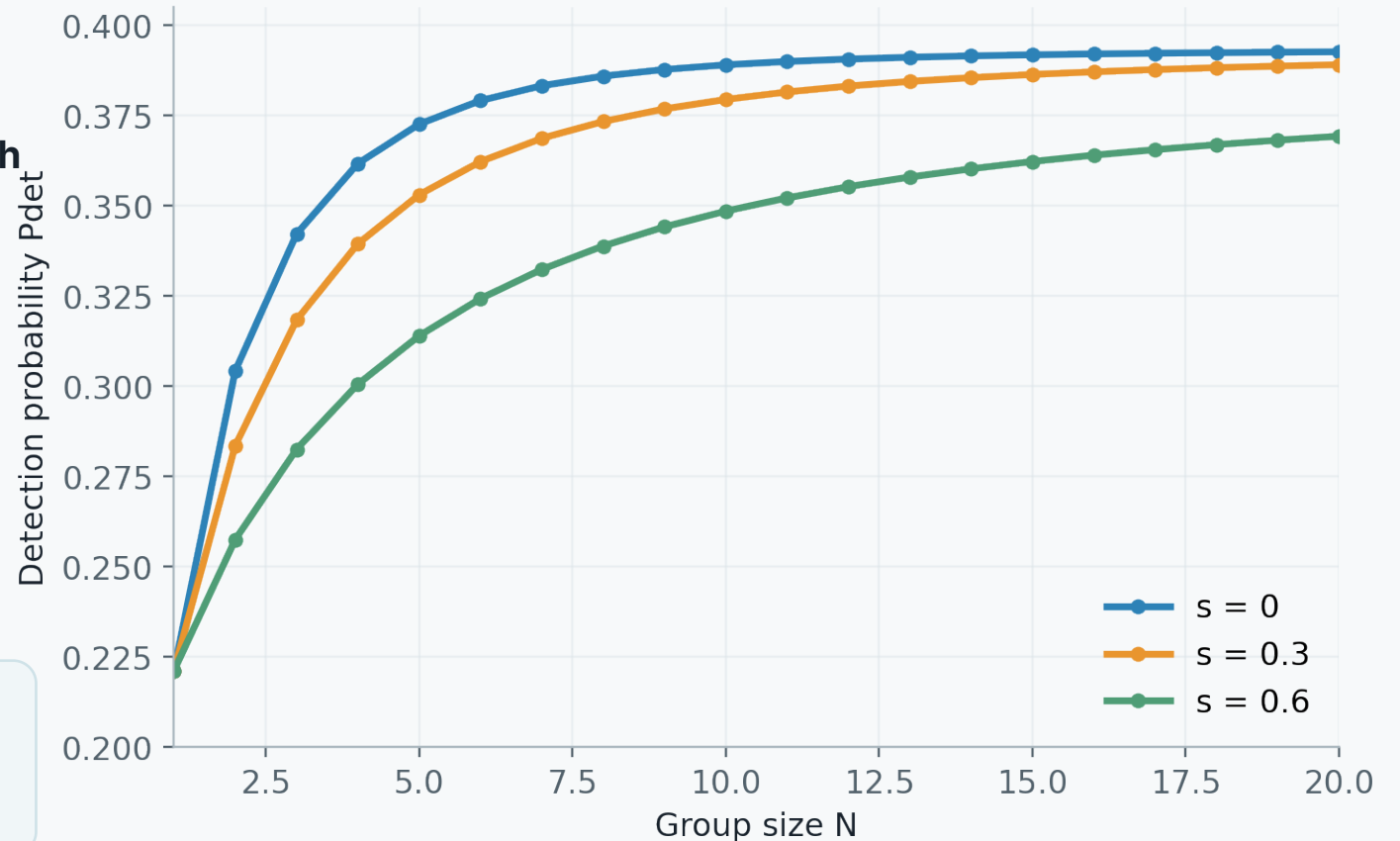
Model 4 — Predator detection

$$P_{\text{det}}(N, t, s) = 1 - e^{-\mu t C(N, s)}$$

Detection events follow a Poisson process with rate $\mu \cdot C(N, s)$.

- More collective vigilance → higher detection probability.
- Longer observation windows also increase detection.
- For fixed parameters, the curve approaches a model-dependent ceiling.

Higher synchronization lowers detection efficiency because fewer watchers add independent information.



Illustrative case: $v_0 = 0.5 \cdot k = 0.05 \cdot \mu = 0.5 \cdot t = 1$

How much does one more watcher buy us?

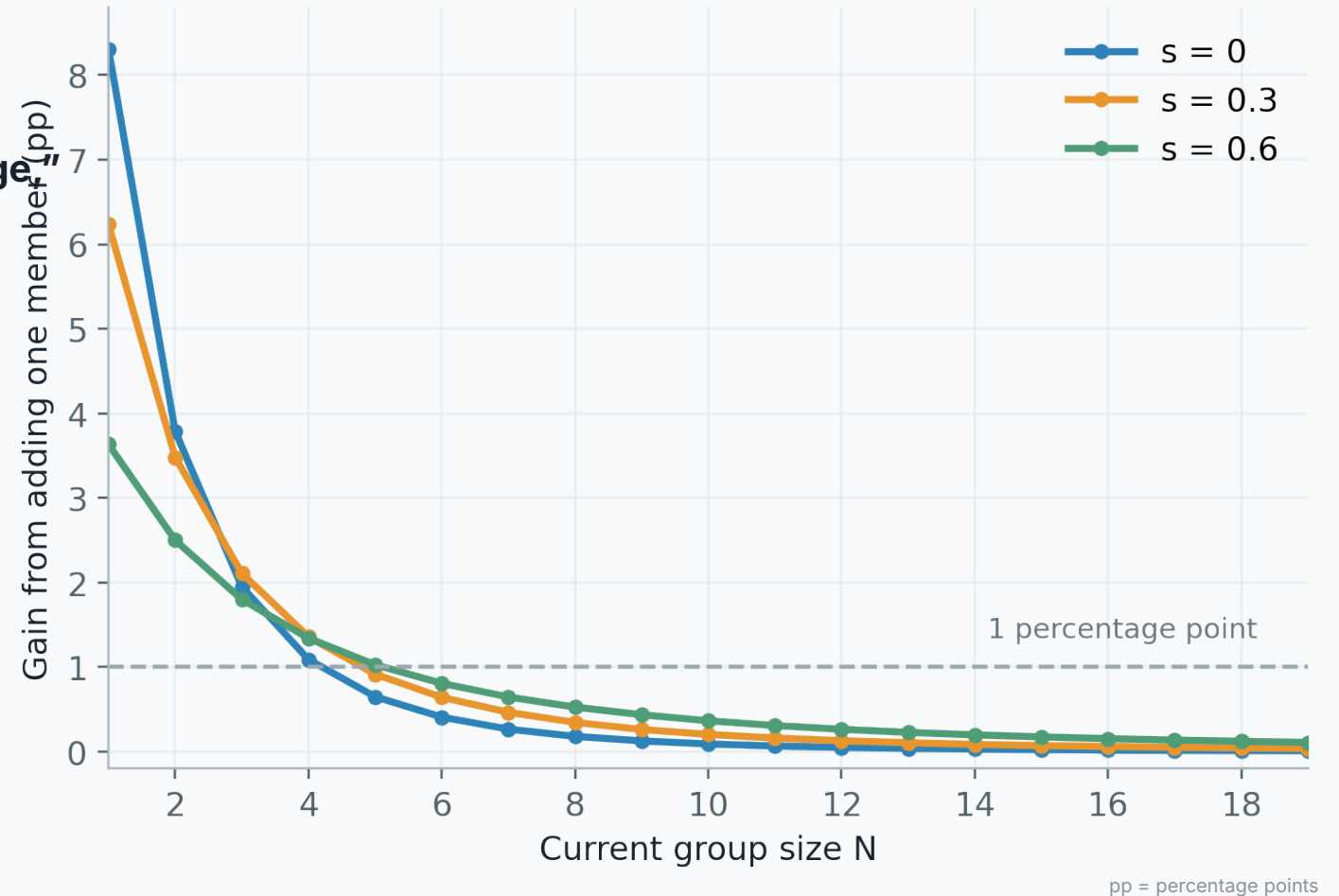
$$\Delta P_{\text{det}}(N) = P_{\text{det}}(N + 1) - P_{\text{det}}(N)$$

Instead of calling a group “moderate” or “large,” measure the marginal gain from the next member.

What the curve tells us

The first few additions produce the largest gains. After that, each new member contributes progressively less - especially when synchronization is high.

Diminishing returns are now quantified, not just described.



What the base model actually supports

01

Group size helps early

Detection rises quickly with the first additions, then marginal gains shrink.

02

Redundancy limits the benefit

The same group size performs worse when scanning behavior is more synchronized.

03

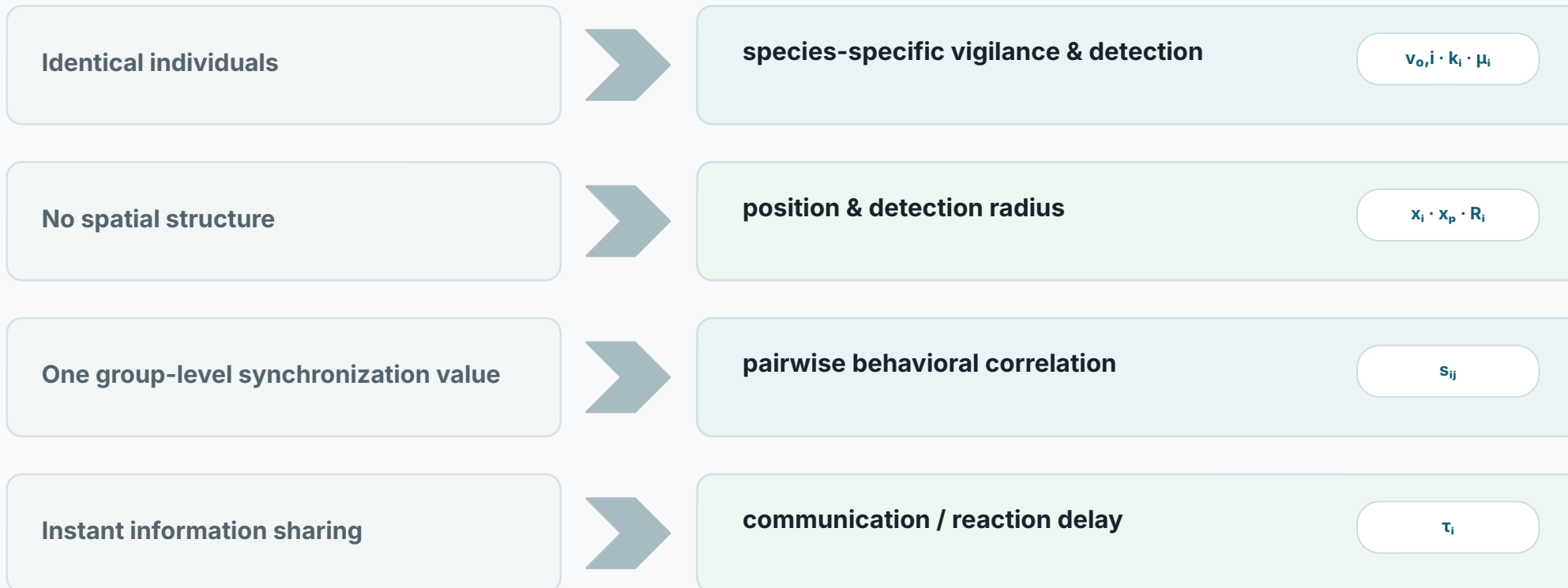
Mixed-species advantage is conditional

Mixed-species groups benefit when species contribute complementary, less-redundant vigilance - not simply because more species are present.

Key shift: species diversity is a mechanism for complementary information, not a stand-alone variable in the base model.

Where the simple model falls short

The analytical model is useful because it is interpretable. It is also deliberately simplified.



The extension tests whether the same independence mechanism survives once individuals differ, space matters, and information is delayed.

Extended model — who can actually contribute?

$$P_{\text{det}}(t) = 1 - \exp \left[- \sum_{i=1}^N \mu_i w_i(N) \delta_i(x_p) t_i^{\text{eff}} \right]$$

An individual contributes only when it can detect the predator and has enough usable response time.

01

Individual differences

Each watcher has its own vigilance and detection ability.

02

Spatial reach

$\delta_i(x_p) = 1$ only when the predator lies inside individual i 's detectable range.

03

Synchronization

$w_i(N)$ discounts redundant vigilance when behavior is correlated.

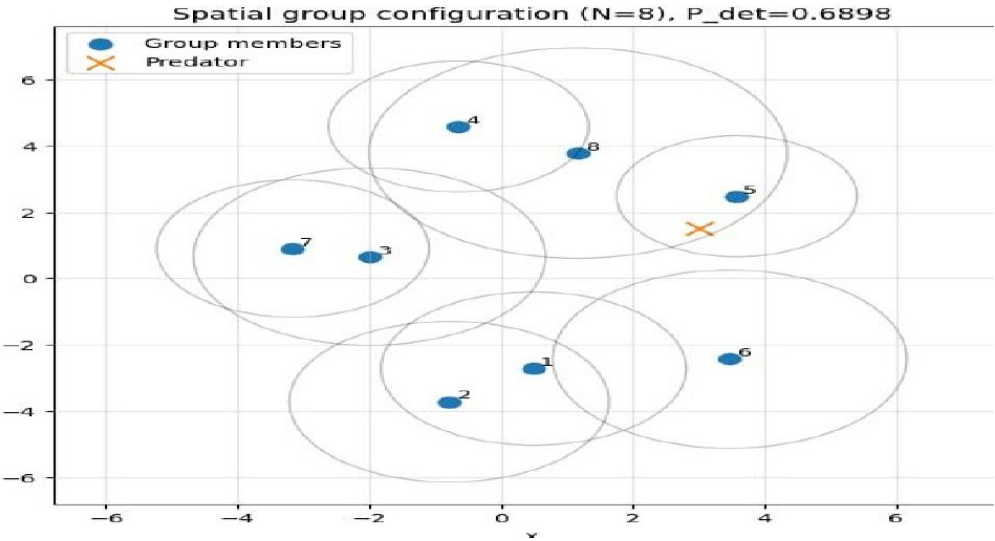
04

Communication delay

t_i^{eff} is the remaining usable time after reaction / information delay.

Extended simulation

Spatial configuration example



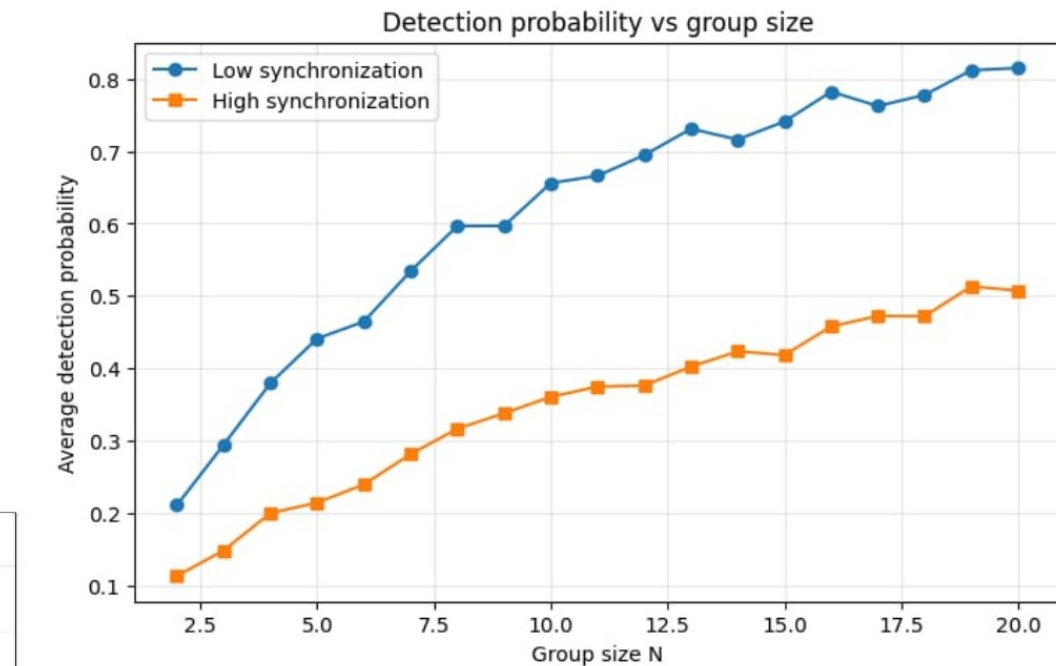
The extended simulation preserves the central pattern:

Detection rises with group size

Low synchronization performs better

Independence matters

Low vs. high synchronization



Conclusions

1

Group size helps most at the beginning

The earliest added watchers produce the largest increases in detection.

2

Redundancy is the limiting mechanism

Synchronization makes additional watchers contribute less independent information.

3

Mixed-species benefits depend on complementarity

Diversity helps when species differ enough in behavior or sensing to reduce overlap.

4

The extended model keeps the same core story

Spatial range, individual differences, and delay change who contributes - but independence still matters.

More watchers help. More independent watchers help more.

Limitations & next steps

Current limitations

Uniform base parameters in the analytical model

Constant group size

Simplified predator approach

Synchronization compressed into a small set of parameters

Where to go next

Calibrate species-specific vigilance and detection rates

Add predator dynamics and movement

Allow changing group composition

Model reaction / communication networks in more detail

A strong next step is empirical calibration: use real species-level data to estimate parameters rather than choosing illustrative values.

References

01

Stears, K., Schmitt, M. H., Wilmers, C. C., & Shrader, A. M. (2020). Mixed-species herding levels the landscape of fear. *Proceedings of the Royal Society B: Biological Sciences*, 287(1918), 20192555.

02

Goodale, E., Sridhar, H., Sieving, K. E., et al. (2020). Mixed company: A framework for understanding the composition and organization of mixed-species animal groups. *Biological Reviews*, 95(4), 889–910.

03

Pays, O., Renaud, P. C., Loisel, P., Petit, M., Gerard, J. F., & Jarman, P. J. (2007). Prey synchronize their vigilant behaviour with other group members. *Proceedings of the Royal Society B: Biological Sciences*, 274(1615), 1287–1291.

Final takeaway

More watchers help.

**More independent
watchers help more.****Questions?**