Time compensation in the celestial compass of insects

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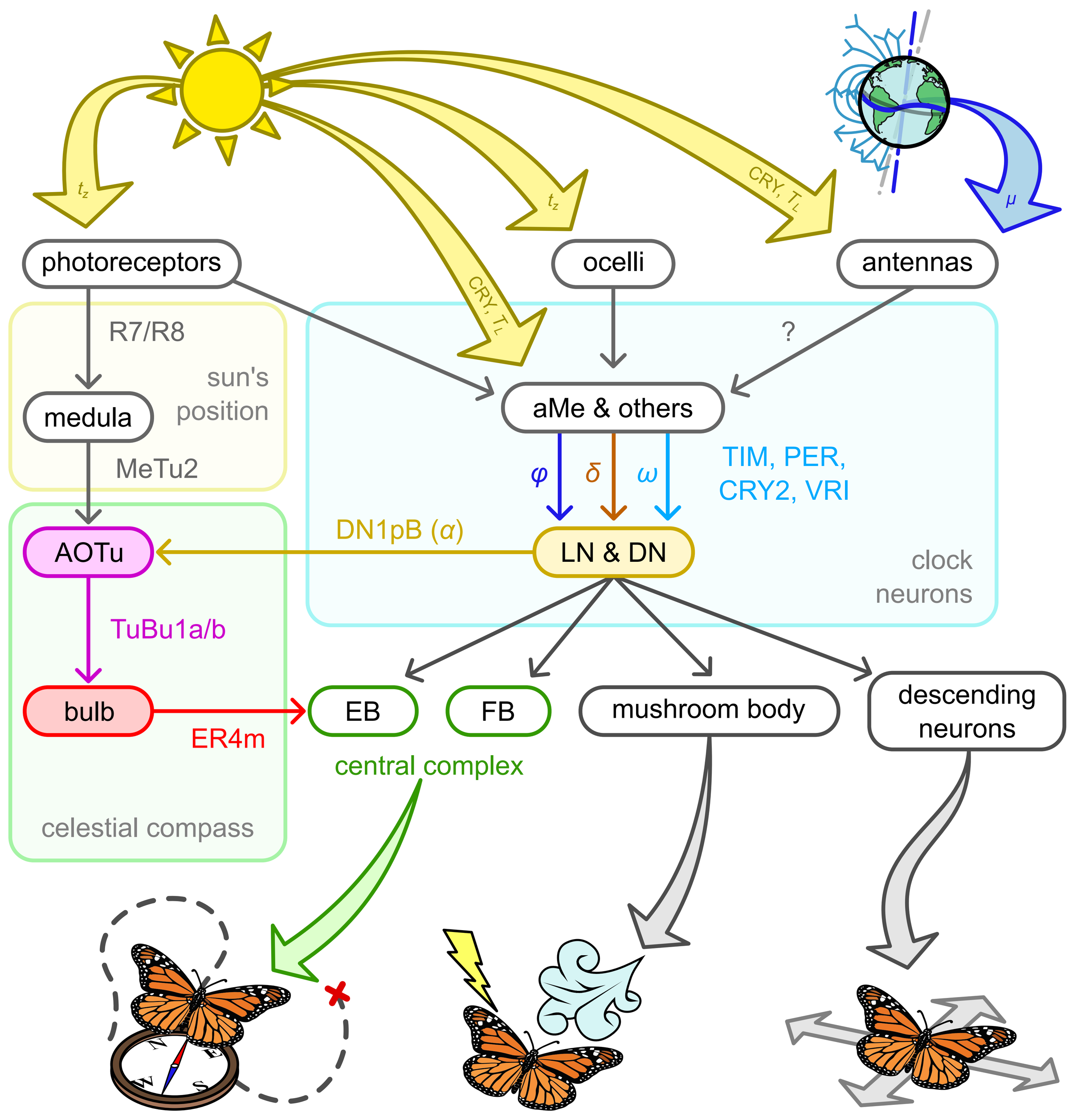
Introduction

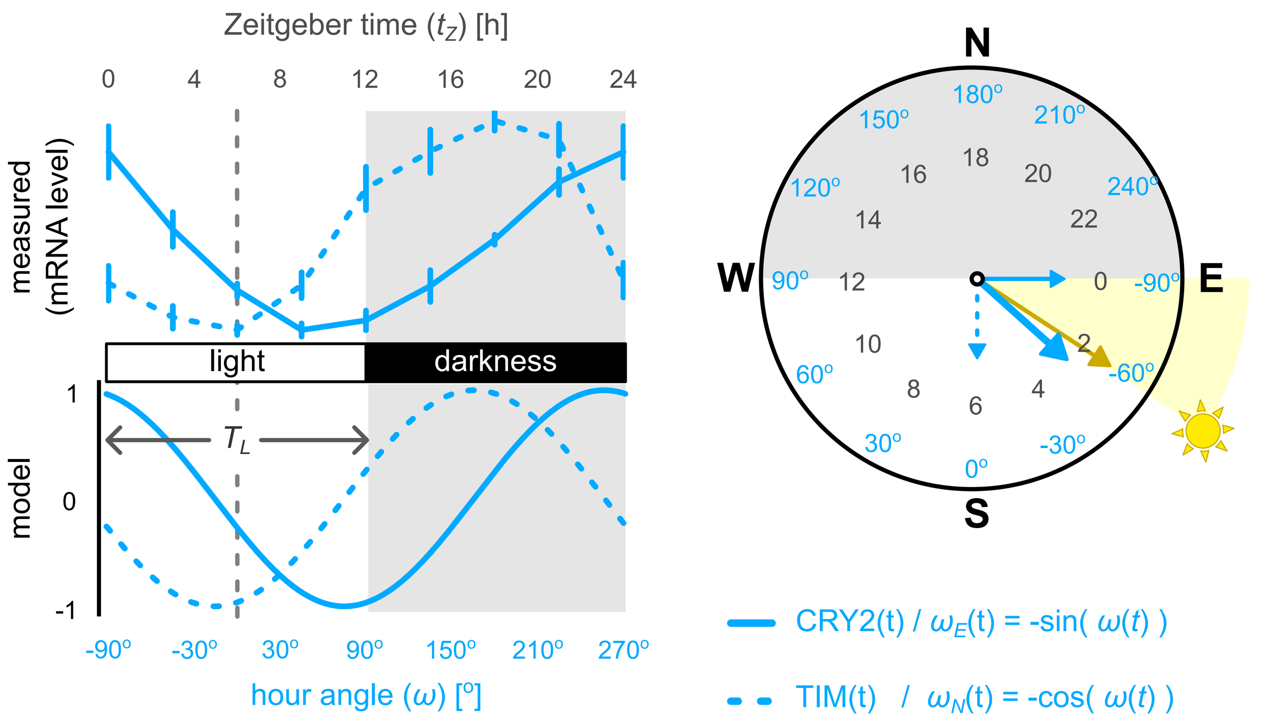
The sun's position must be time-compensated to become a geocentric compass.

We explore the time compensation mechanism in the insect brain, and present:

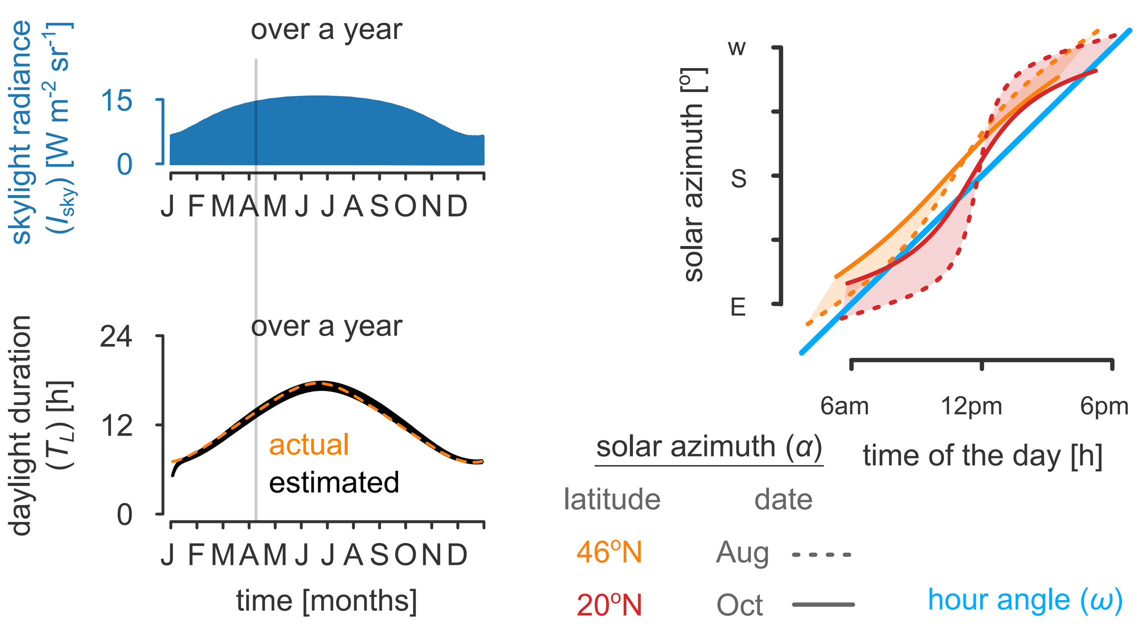
1. Two models that can track the sun in different levels of precision,
2. A time-compensation mechanism based on trigonometric identities,
3. Simulations of foraging and migrating insects using both models.



The hour-angle model (ω)



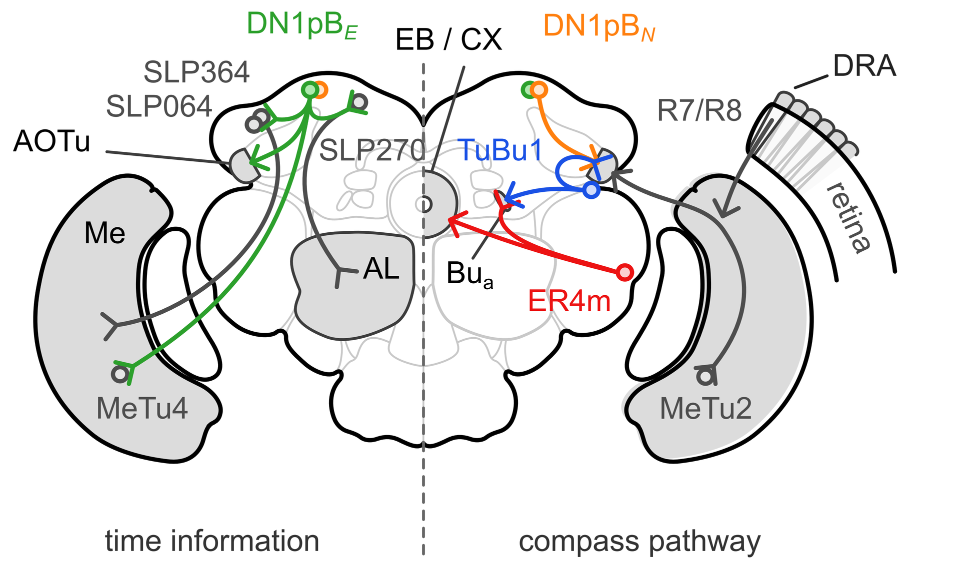
DN1pB activity oscillates during the day, resembling clock proteins [5].



Oscillations must adjust for the daylight duration.

Hour angle must adjust for time of the year and latitude.

Celestial compass and clock neurons

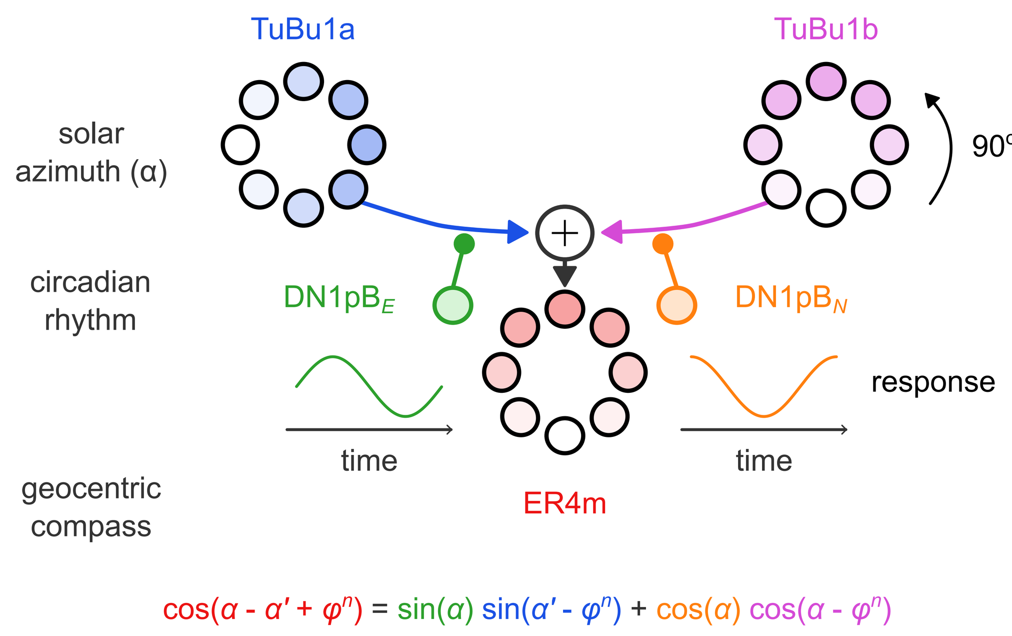


The sun is detected by photoreceptors in the compound eyes.
Downstream TuBu1 neurons represent the sun [1] (model [2]).
Two DN1pB neurons represent time in *D. melanogaster* [1, 3].
Time is synchronised using daylight [4].

References

[1] B. J. Hardcastle *et al.* *eLife*, vol. 10, p. e63225, 2021.
[2] E. Gkanias *et al.* *Communications Engineering*, vol. 2, no. 1, p. 82, 2023.
[3] B. K. Hulse *et al.* *eLife*, vol. 10, 2021.
[4] C. Merlin *et al.* *Science*, vol. 325, no. 5948, pp. 1700–1704, 2009.
[5] E. Shlizerman *et al.* *Cell Reports*, vol. 15, no. 4, pp. 683–691, 2016.

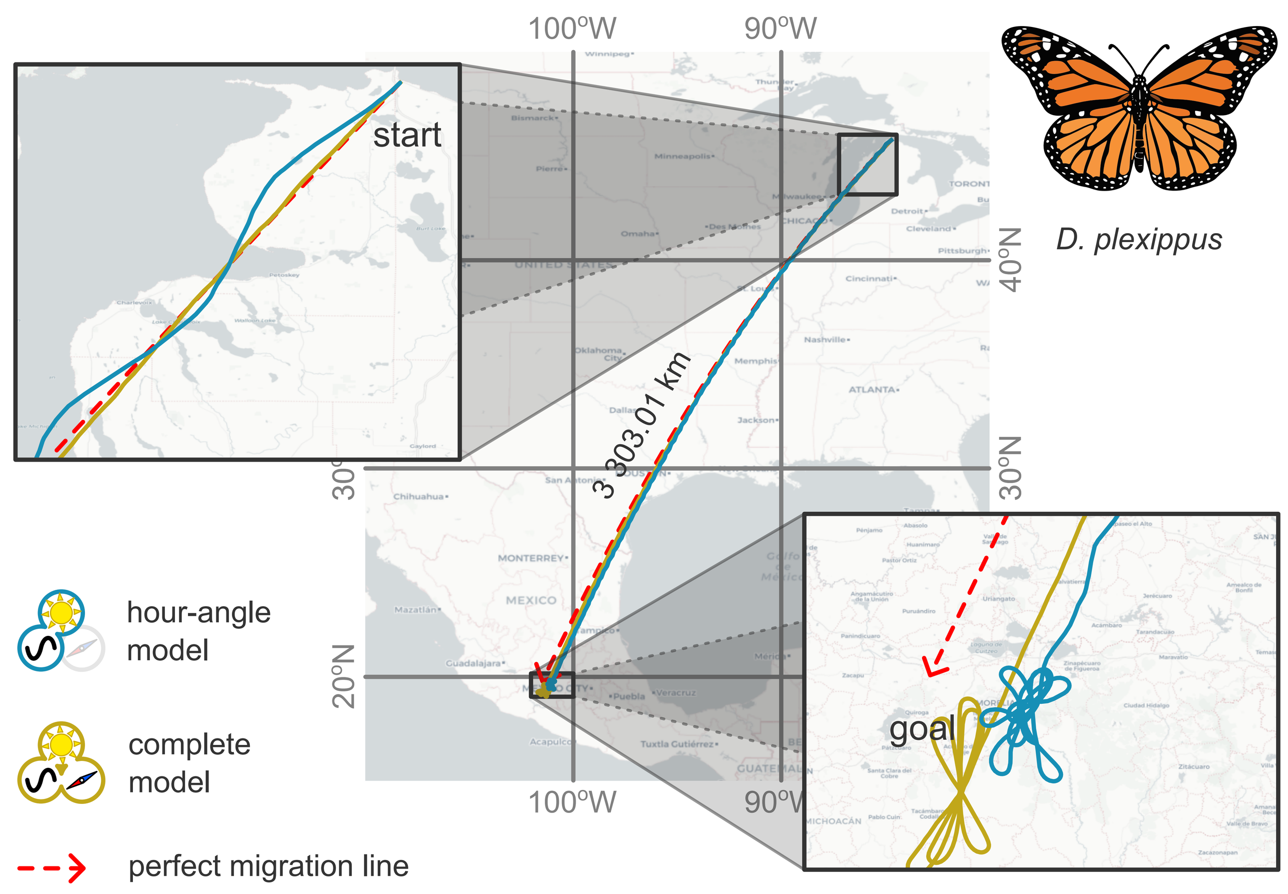
Compensation for the moving sun



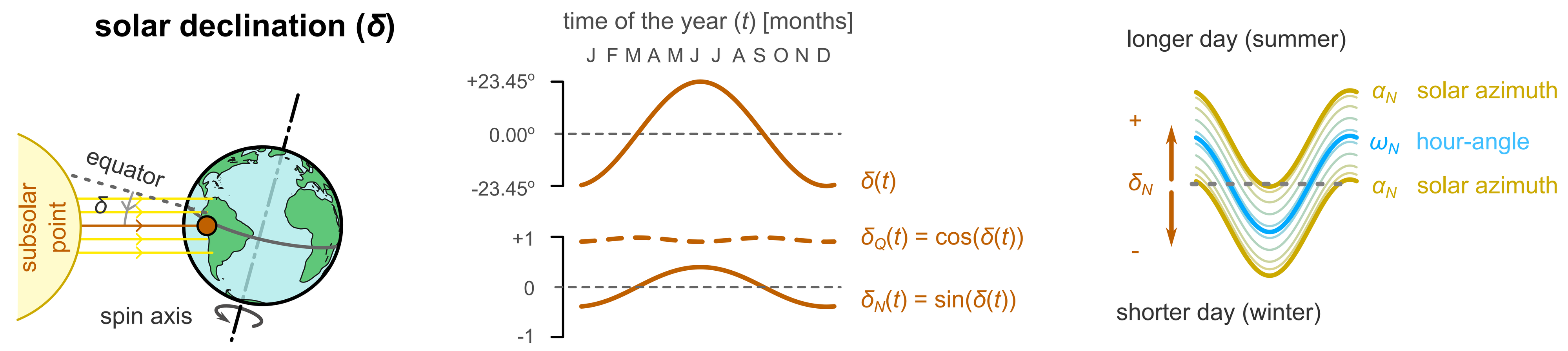
$\cos(\alpha - \alpha' + \varphi^n) = \sin(\alpha)\,\sin(\alpha' - \varphi^n) + \cos(\alpha)\,\cos(\alpha - \varphi^n)$

TuBu1a/b populations represent the retinotopic sun's position [2].
A 90° phase-shift encodes the sine and cosine of the head-sun angle.
Similarly, DN1pB$_{E/N}$ neurons predict the north-sun angle in time.
Their responses combine using trigonometry into a celestial compass.

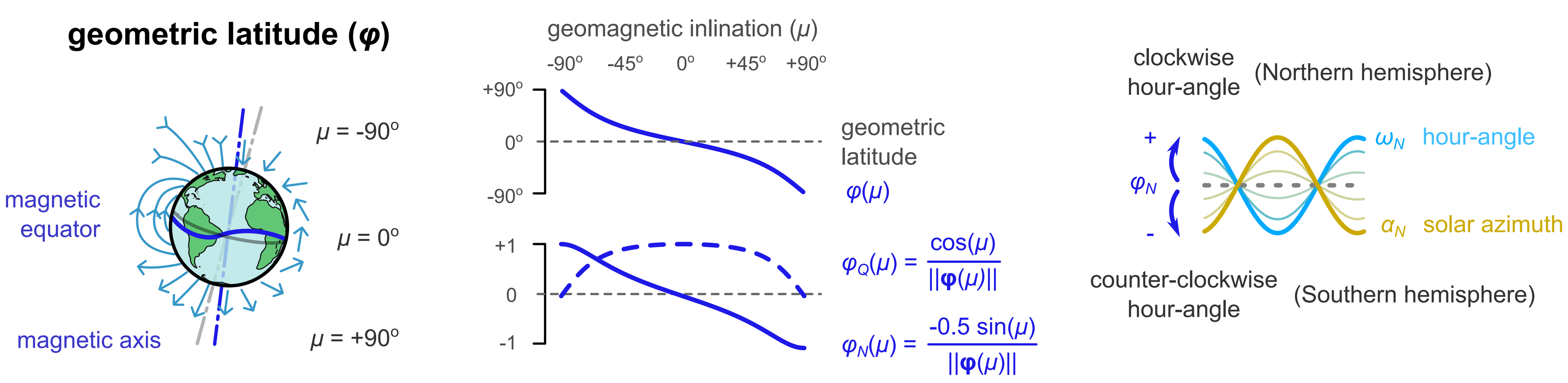
		hour angle		complete
DN1pB$_E$	is	ω_E	or	α_E
DN1pB$_N$	is	ω_N	or	α_N



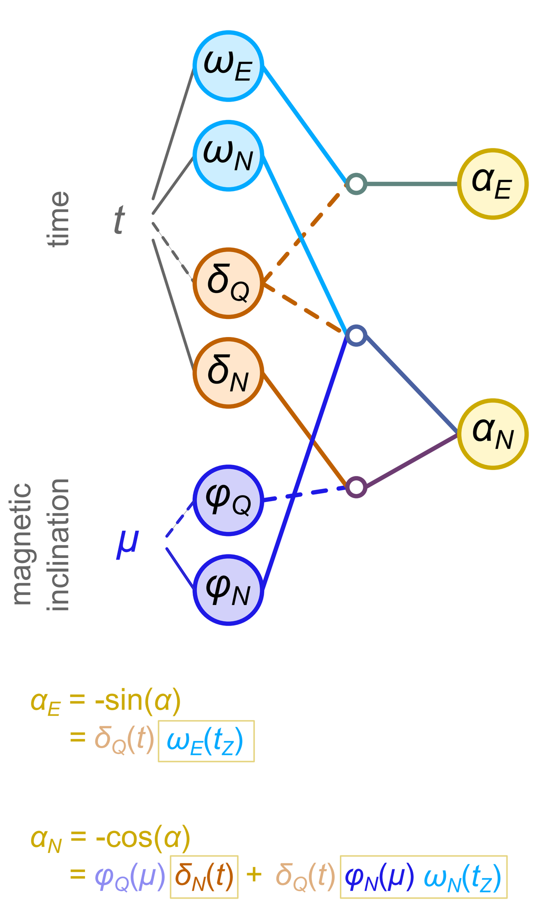
The complete time-compensation model (α)



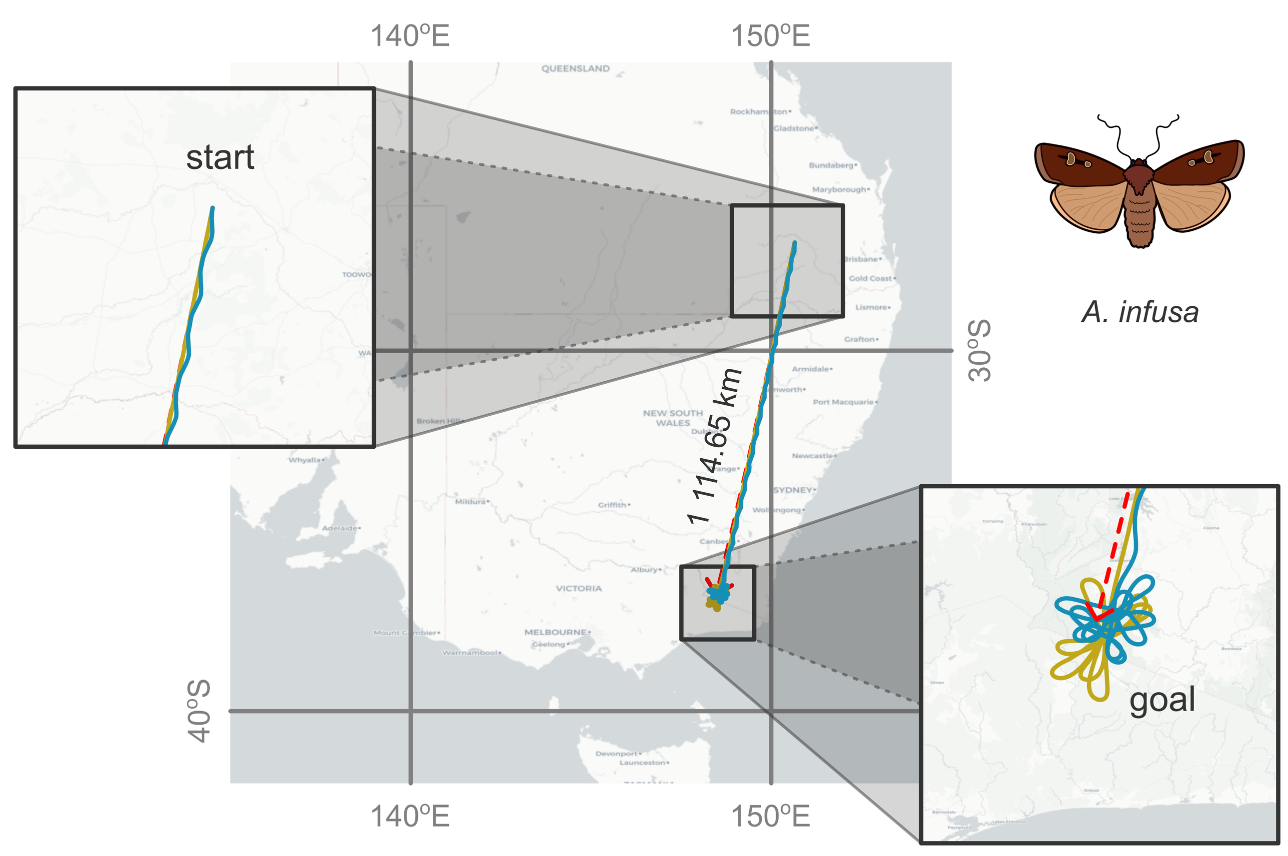
A couple of annual clock neurons can estimate the solar declination, representing the seasonal changes in daylight duration.



The geometric latitude is a monotonic function of the geomagnetic inclination and represents the direction of the hour-angle.



Representation of the north-sun angle.



Simulations of central-place foraging and migration

Both models are sufficient for foraging when combined with landmarks.
The hour-angle model can explain migration in both hemispheres.
The complete model is needed when insects cross the equator.