

Title: Sleep homeostasis, circadian rhythms, and stochasticity reveal hierarchical entrainment mechanisms

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Objective: Chronotype, often measured as mid-sleep on free days, reflect an individual's preferred sleep and wake timing and are commonly interpreted as a proxy for circadian phase. The intrinsic circadian period is a major determinant of chronotype, with longer periods associated with later chronotypes. This conception is generally used to explain abnormal chronotypes (extreme eveningness or morningness) as susceptibility to extreme circadian period. However, a subtle discrepancy remains: chronotype distributions worldwide are typically right-skewed, whereas intrinsic circadian period distributions are slightly left-skewed, suggesting a revision of assumptions about this strong linearity.

Methods: We modified the Borbély two-process model of sleep regulation to computationally simulate how interindividual differences in the buildup and dissipation of sleep pressure (Process S) together with realistic circadian period distributions (Process C) shape chronotype variation. Stochasticity in the sleep pressure buildup with positive determinant shift adds variance to Process S and yields a right-skewed chronotype distribution. Error estimates of the distance between simulation and targeted large-scale chronotype distribution are used to explore the parameter space.

Results: Exploring the parameter space by varying circadian amplitude reveals an Arnold tongue, indicating that the skew emerges from the hierarchical entrainment of Process S to Process C, which is in turn entrained by light. Our simulations confirm a general positive relation between intrinsic period and circadian phase within the normal range, while reproducing larger, asymmetric variability at short and long periods. This preserves the correlation but alters the distributional skew. These findings suggest that chronotype emerges from the nonlinear interaction between the homeostatic sleep process and a hierarchically entrained circadian system.

Conclusion: According to our findings, pathological chronotypes cannot completely be mapped to an individual's intrinsic circadian period and instead reflect Arnold tongue-like synchronization dynamics between the sleep-wake oscillator and the circadian oscillator. Our results caution against inferring intrinsic circadian period solely from chronotype, particularly in clinical contexts where accurate assessment of circadian rhythmicity is critical.

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