NC challenge: Problem 2

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The problem

The aim of this problem is to investigate whether a ring that measures temperature during the night can provide a viable temperature reading for the Natural Cycles (NC) app. The current method of predicting fertility relies on monitoring the basal body temperature (BBT) (lowest core body temperature (CBT) by a temperature reading upon waking using a standard two-digit thermometer. Thus a single 'clean' temperature that can be passed to the NC algorithm should be extracted from each nightlong measurement. For the full period of the study (a little more than two cycles) this 'clean' temperature should be compared to the corresponding standard thermometer readings taken over the same time period. I assume that in order for a 'clean' temperature to be viable it must have a reasonable correlation with the thermometer readings, but that an offset in absolute value would be tolerated by the NC algorithm. In order to have some correlation the ring temperature the 'clean' temperature will have to show a cyclic variation with the same period as the core body temperature.

Raw data: Ring

The data from a sample night is shown in the top panel of figure 1 and is quite representative of an average night. The ring records a measurement every 60 seconds between well defined switch on/off times. I use these times to define the length of the

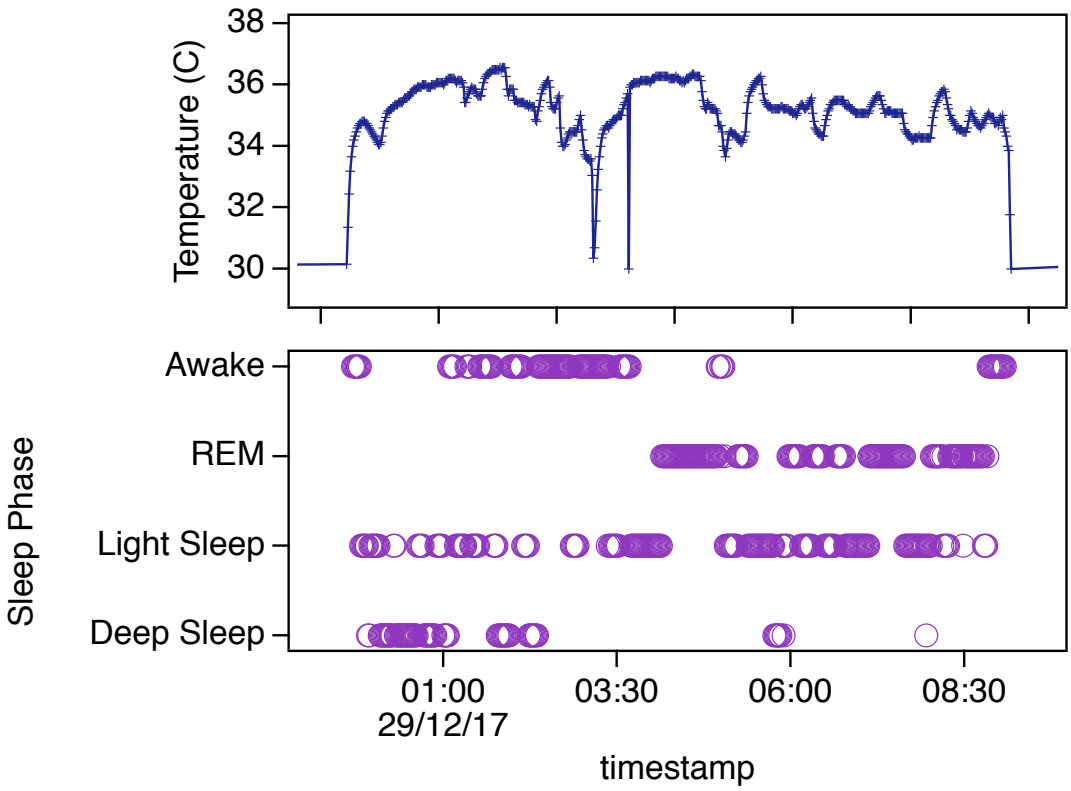

Figure 1 Top Panel: Raw temperature data from ring on a sample night. Lower panel: raw Sleep Phase data from the ring on a sample night.

night, which I assume is similar to the time spent sleeping. There is a warm-up and cool-down temperature ramp as the ring takes a few minutes to thermalize to the cycler's finger. During the night the ring appears to fail twice, giving spikes of low temperature. During the night the ring reading fluctuates over the order of 2°C on the scale of an hour and has many sudden temperature jumps. It would be useful to have additional data about the performance of the thermometer (for example a controlled study of use by the manufacturer) that could aid in understanding the nature of these jumps. They could be due to environmental factors such as the user moving around, or they could be essentially noise. I assumed that the cycler did not remove the ring during the night, and did not wear the ring while awake. The ring temperature does not show any strong trend over the night. In particular it does not show a minimum that could be associated with the expected drop in core body temperature during the night. Indeed it is known that the skin temperature does not track the core body temperature during the night [1].

The sleep phase data shown for the same night in the lower panel figure 1 also shows many variations that do not appear to be strongly correlated with the temperature readings over short timescales (tens of minutes). However, I did see that over the full data set (not shown) that the 'awake' sleep phase has much larger temperature range extending to lower temperatures than the other three sleeping phases. It may be instructive to know whether sleep phase is determined independently of the temperature or if the two measurements are dependent.

Raw data: Thermometer

The morning measurements of temperature taken over the course of the study are shown as the dark magenta trace in Figure 2. The period start dates are show by vertical bars. The luteal and follicular phases have a temperature difference of approximately 0.5 C and are evident from the temperature rise in the second half of the cycle, before the period start dates.

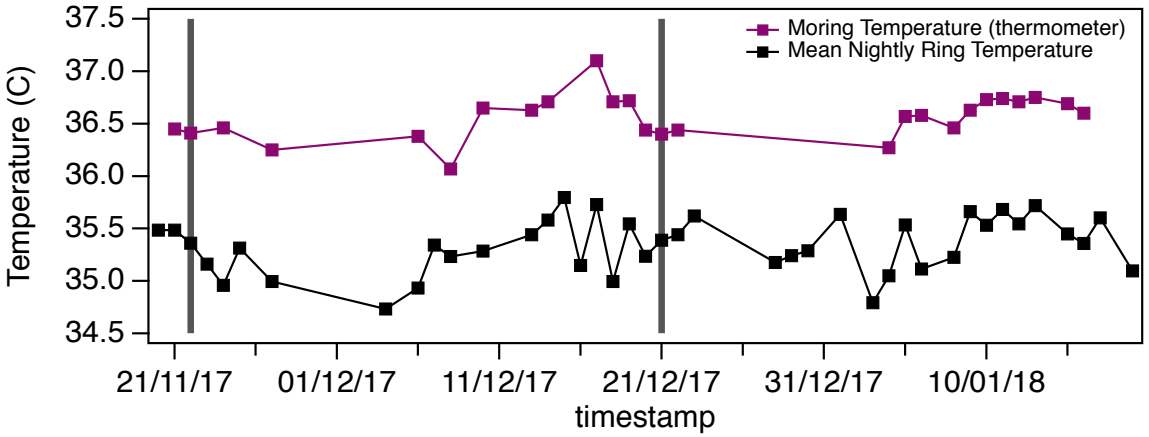

Figure 2 Raw data from the two-digit thermometer morning temperature readings (dark magenta) and a 'clean' temperature extracted from the ring temperature data (black). The 'clean' data is a mean of the nightly measurement without 'fail' measurements included.

Analysis of Ring Data

Due to the strong fluctuations in temperature during the night it does not seem reasonable to try to pin-point a single measurement as the waking temperature of the ring. Rather it is

clear that the 'clean' temperature will have to be some kind of mean over the nightly temperature readings. To quantify the correlation between the thermometer measurements and the 'clean' ring temperature of the same date, I will calculate the linear and spearman's rank correlation coefficients.

The black trace in Figure 2 is the nightly mean temperature for all nights in the study. This mean was calculated from all readings except for the 'fail' measurements. The threshold for fail measurements was set at 32.5 °C. In this context, 'raw' means no data points during the night have been removed or modified before the mean was taken. Skin temperature is known to have a lower absolute value to core body temperature[1], which is demonstrated in Figure 2. The raw-mean does not show such a strong temperature change as the thermometer reading between the follicular and luteal phases and seems to have stronger variation from night to night.

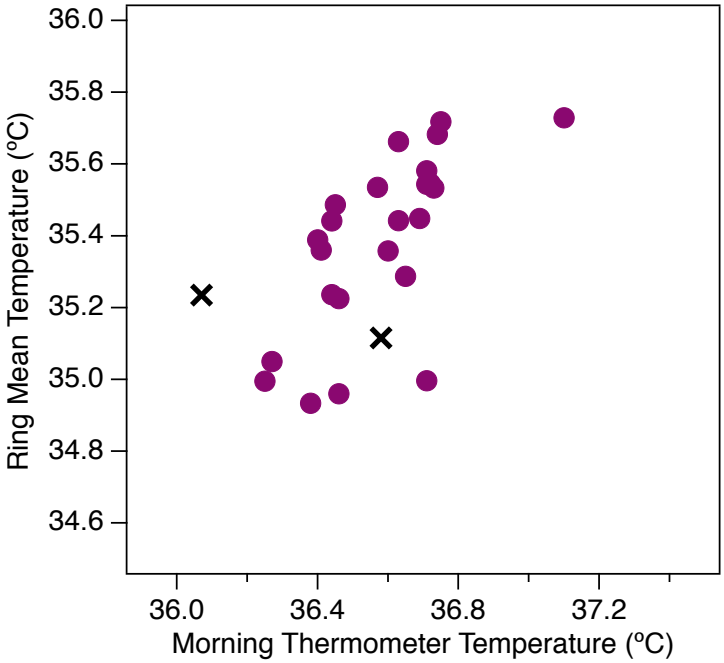

Figure 3 Scatter plot of the mean nightly temperature as 'clean' ring temperature and the thermometer morning measurements. The crosses are points corresponding to nights that were longer/shorter than the average sleep time of 9 hours by more than 2 hours, or were deemed very wakeful due to a high mean sleep phase.

As an example, Figure 3 shows a scatter plot of the thermometer readings and the corresponding mean nightly temperature. This has a Spearman's rank coefficient of 0.70614. By rejecting nights that were deemed too wakeful or too long the points shown by a cross were discounted. This subset of points had a Spearman's rank coefficient 0.73024, a slight improvement. A night was deemed too wakeful if the mean sleep phase for that night was above a threshold value. A night was deemed too long if it was 2 hours longer or shorter than the nominal length, which here was chosen to be 9 hours. In this analysis the explicit impact of removing abnormal length nights cannot be seen since the long nights either coincided with the wakeful nights or were not in the subset of temperatures the corresponded to thermometer readings.

I saw no measureable impact of removing the warm-up cool-down ramps on the correlation of the 'clean' ring temperature with the thermometer readings because they are such a small fraction of the total nightly readings. In contrast, Removing 'fail' measurements is important as there are some nights where the ring fails for hours at a time. An impact on correlation would only be seen if these fail nights coincide with thermometer measurements. Removing fail measurements from a normal night has very little impact.

Table 1 summarizes correlation of the thermometer readings with the five candidate 'clean' ring temperatures I considered. Fail nights are rejected for all 'clean' temperatures. The nightly mean with wakeful nights rejected has the highest correlation with the thermometer readings. The sleeping mean is the mean ring temperature considering only points that corresponds to a sleep phase less than 4. Sleep phase 4 ('awake') has a larger associated temperature range however removing the 'awake' measurements actually reduced the correlation. The morning mean is a mean over some fixed time before the ring turns off in the morning. For times of 5, 20 and 30 minutes the morning mean had a correlation of around 0.63. For a morning mean taken over 1 our before waking, the possibility of non-correlation could not be rejected.

	Linear Correlation Coefficient	**Spearman's Rank Correlation Coefficient**
Nightly mean	**0.38824**	**0. 70614**
Nightly mean, wakeful nights rejected	**0.40439**	**0.73024**
Nightly median	**0. 38824**	**0.61737**
Nightly "sleeping" mean	**0. 38824**	**0.63837**
Morning mean	**-**	**-**

Table 1 Correlation coefficients of five candidate 'clean' temperatures with the thermometer reading.

Conclusions

The correlation of the 'clean' ring temperatures and the thermometer readings is not high. My feeling is that even the best 'clean' temperature I found would not be good enough to use as a substitute for standard daily thermometer readings. However, to judge this properly would require insight into the NC algorithm. That being said, there is some correlation, which suggests that while the skin temperature does not track the CBT during the night, it does have some periodic behaviour associated with the periodic nature of the CBT over a menstrual cycle. Therefore the data suggest that some kind of nightly skin measurement could work. Perhaps the finger is not a good choice of where to measure, or perhaps, keeping in mind the temperature jumps in figure 1, this ring device is not stable enough. To distinguish these cases more information about the ring device is needed and similar analysis of data from other devices is needed.

References
1. Kräuchi, K. Clinical Autonomic Research 147-9 (2002)