Student name : **Student number :**

Coordination Dynamics: Principles and Applications

Optional interim exam 2016-2017

Closed book exam
21-11-2016
15:30–17:30h
MF-FG1

Please write on each sheet of paper your name and student number. The exam consists of several open questions, for which in total 35 points can be earned. Concise answers are highly appreciated and sufficient to earn the points. The Notes section on this page provides additional space to answer questions in case the provided space is insufficient. Please note that erroneous passages in a lengthy answer may have adverse consequences in that they can lead to diminution of points you received for correct parts in the answer.

Good luck!

Notes

Model answers

Question 1: HKB-model of coordination dynamics (10 points)

The Haken-Kelso-Bunz (HKB) model of coupled oscillators is one of the foundations of coordination dynamics, an empirically grounded theoretical framework that seeks to understand coordinated behavior in living things. The HKB model was originally formulated in 1985 to account for some novel experimental observations on human bimanual coordination (Schöner & Kelso, 1988; Kelso, 1995) that revealed fundamental features of self-organization such as multi-stability, phase transitions and symmetry breaking. These features are captured by HKB's

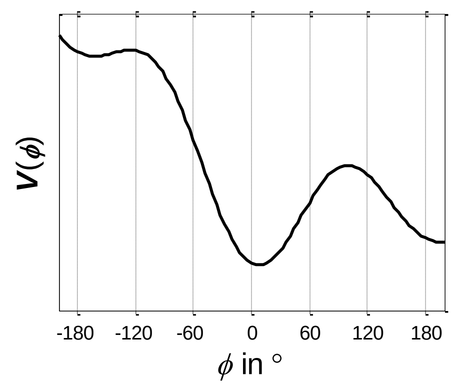
- order parameter dynamics equation: $\dot{\phi} = \Delta\omega - a\sin(\phi) - 2b\sin(2\phi) + \sqrt{Q}\zeta_t$
- potential: $V(\phi) = -\Delta\omega\phi - a\cos(\phi) - b\cos(2\phi)$.

a) What is the frequency relation between the coupled oscillators in a symmetric HKB-model with non-zero b and a? Explain. **[1 point]**

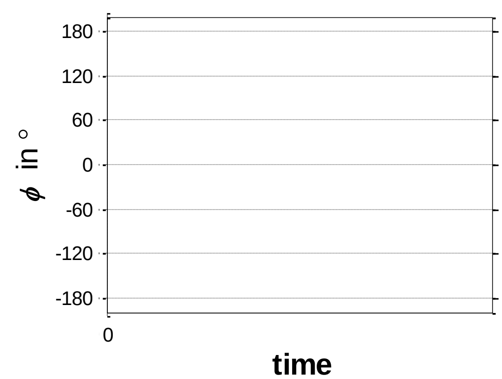
For a symmetric HKB model Δω=0 and with non-zero a and b there is always at least one stable solution, implying phase locking for all parameter values. Hence, the two oscillators must be frequency locked, in a 1:1 relation (both oscillators move at the same frequency).

b) In the upper panel of the figure a HBK potential is depicted for a non-zero *Δω* with *b*/*a* = 0.7. Is *Δω* positive or negative in this figure? Explain. **[1 point]**

Delta omega is positive, see the first term in the equation for V(phi) representing the linear trend as a function of phi (note the minus sign in front of delta omega)



c) Plot in the lower panel of the figure the evolution of the order parameter ϕ over time for initial values of ϕ: -180°, -120°, -60°, 0°, 60°, 120°, 180°. **[4 points]**



fixed points are located at +10 and at -170 degrees, approximately. Lines should be drawn towards these fixed points as a function of time, starting at the 7 initial values on the vertical axis. 180, 120 and -180 go to -170, -60, 0 and 60 go to 10 and -120 can go both ways (unstable fixed point). Time course is different for +10 (faster) than -170 (slower) attractors

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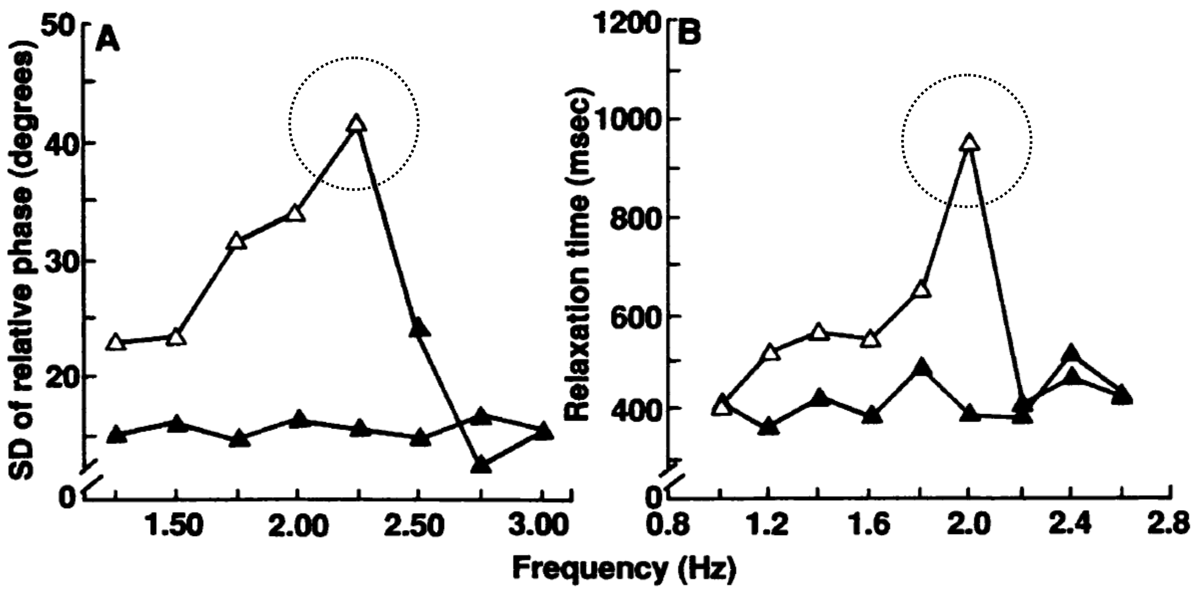
d) Is there a single, unique value of ϕ for each combination of non-zero $\Delta\omega$, a, b and Q? Explain. **[2 points]**

No. The HKB model is a model with two stable solutions for b/a values > 0.25, indicating that for a given combination of abovementioned parameters, phi can be either in the in-phase mode of coordination or in the antiphase mode of coordination (multistability). Moreover, within a stable mode, phi will vary as well if Q>0 (Noise). In the bistable regime, phi also depends on the direction of parameter changes (hysteresis). Finally, for certain parameter values relative coordination occurs (no stable fixed points), for which phi can result in all possible values (phase wrapping). Ergo, there is never a single unique value for phi for a given set of parameter values.

e) In their Science paper, Schöner and Kelso (1988) formulated 5 theoretical propositions to explain pattern formation, stability and change. Their loss of stability proposition was accompanied by the following figure, with encircled two key empirical findings as a transition is approached. Write the names for these two phenomena in the respective figure panels. **[2 points]**

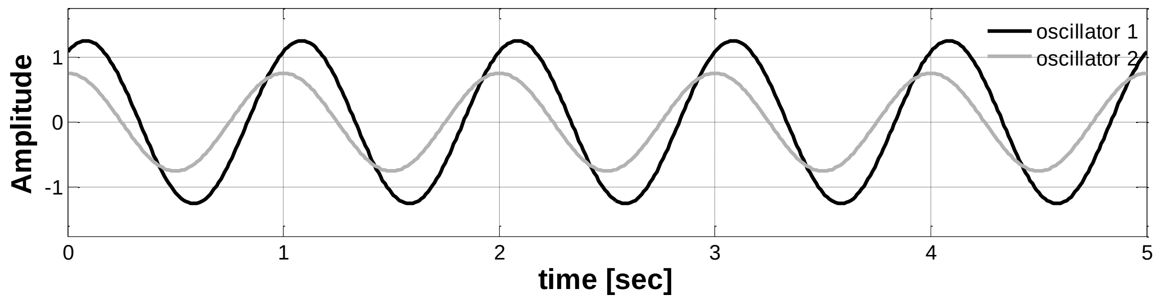


A: Critical fluctuations, B: critical slowing down

Question 2: Relative phase (3 points)

There are two ways to determine relative phase to describe coordination between two oscillators.

1) Continuous relative phase $\varphi_{continuous,}$ that is the difference in phase evolution of two oscillators for each point in time, using $\varphi_{continuous} = \varphi_{oscillator1} - \varphi_{oscillator2}$.
2) Discrete relative phase $\varphi_{discrete}$, that is the time latency of one oscillator relative to the other divided by the oscillation period, evaluating coordination at a specific point in each oscillation cycle (hence also known as the point estimate of relative phase). The discrete relative phase follows from $\varphi_{discrete,i} = 360°\cdot(t_{oscillator2,i} - t_{oscillator1,i})/(t_{oscillator1,i+1} - t_{oscillator1,i})$, where $t_{oscillator1,i}$ indicates the time of the ith maximum in the cycle of oscillator 1 and $t_{oscillator2,i}$ corresponds to the moment of the ith maximum in the cycle of oscillator 2.



a) In the figure above, trajectories of oscillators 1 and 2 are depicted. As you can see, there is a phase shift between the two oscillators. Which oscillator is leading? **[1 point]**

Oscillator 2 is leading, it arrives at its extrema earlier than oscillator 2 does (amplitude does not matter for phase lead/lag).

b) Which one of the following four options agrees with abovementioned definitions for $\varphi_{continuous}$ and $\varphi_{discrete}$? Briefly motivate your answer. [**2 points**].

1) $\varphi_{continuous} = 30°$ and $\varphi_{discrete} = 30°$
2) $\varphi_{continuous} = 30°$ and $\varphi_{discrete} = -30°$
3) $\varphi_{continuous} = -30°$ and $\varphi_{discrete} = 30°$
4) $\varphi_{continuous} = -30°$ and $\varphi_{discrete} = -30°$

Option 2 agrees with definitions. Continuous relative phase is defined at each time point. Let's examine the phases at t = 1. Oscillator 2 is at its maximum (for which we know that the phase angle is -360, i.e., phase becomes negative as a function of time, each cycle - 360 degrees), whereas oscillator 1 is near its maximum (so phase not yet -360 degrees, but let's say -330 degrees). Hence, continuous relative phase = -330 - - 360 = +30 degrees. Discrete relative phase was based on maxima. Around t = 1 one can see that oscillator 1 reaches its peak at about 1.1 sec and oscillator 2 at 1.0 sec. Oscillation period is 1 second. Hence, discrete relative phase is 360 x (1 - 1.1) / 1 = -36 degrees, so -30 degrees matches best.

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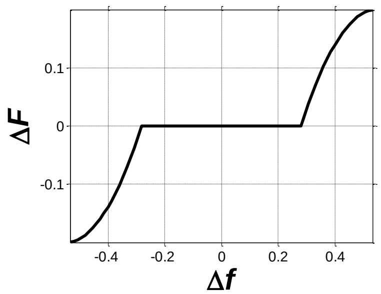
Question 3: Synchronization and coupling (7 points)

Coupled oscillators are seldom identical. Synchronization can be understood as an adjustment of rhythms of oscillating objects due to their weak interaction. Whether or not two non-identical oscillators (having their own frequencies f_1 and f_2) start to oscillate with a common frequency depends on 1) how weak (or strong) the interaction is and 2) how different the uncoupled oscillators are. Consider the schematic *frequency synchronization* vs. *frequency mismatch* plot (ΔF vs. $\Delta f = f_1 - f_2$) for two interacting oscillators. Oscillator 1 has a characteristic frequency f_1 of 1.9Hz while oscillator 2 has f_2 of 2.3Hz.



a) Estimate, based on this plot, what the frequencies are of the two oscillators when coupled. Explain your answer. **[3 points]**

Deltaf is -0.4 and the corresponding value of deltaF is -0.14. Oscillators are only coupled if deltaF is zero, which is for the specified oscillator characteristic frequencies not the case. Nevertheless, both oscillators adjust their frequencies, as delta F is smaller in magnitude than delta f (-0.14 vs -0.4). the slower oscillators speeds up, and the faster one slows down a bit, in such a manner that the difference becomes -0.14.Many answers possible, for example:f1 = 2.0, f2 = 2.14. At least f1>1.9, f2<2.3, f1<f2 and f1-f2 = -0.14

b) When two oscillators are frequency locked, they also have a certain phase relation. However, frequency locking may also happen by chance. How can you experimentally test whether the corresponding phase locking is a matter of chance or instead a genuine effect of coupling? [**2 points**]

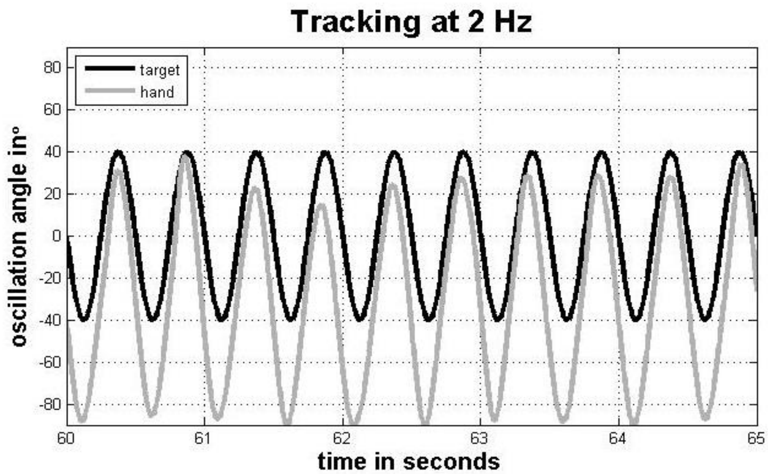
perturb the phase of one oscillator and see if the relative phase returns to preperturbation values. Another option is to start both oscillators a number of times and see of the relative phase converges to similar values across attempts.

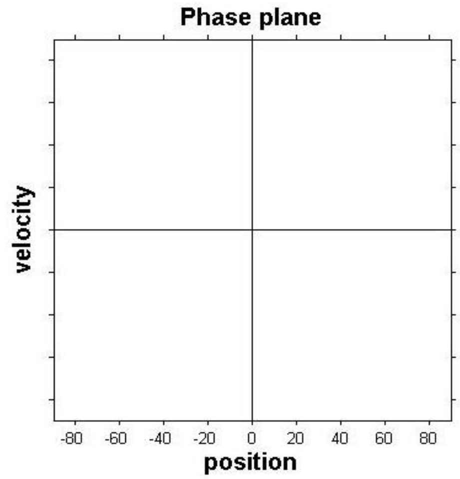
c) In his article “On the self-organizing origins of agency”, Kelso (2016) described agency as a transition. Exchange of information (coupling) proved fundamental in becoming an agent. Explain the type of coupling involved. **[2 points]**

The coupling is mechanical (string between baby’s leg and mobile) and unidirectional (only movements of the baby affect motion and sound of the mobile).

Question 4: Phase planes (7 points)

Phase planes are often normalized to maintain a consistent aspect ratio for all oscillation periods. In the manuscript by Wimmers et al. (1992), participants performed a visuomotor tracking task. A right-handed participant was instructed to manually track a horizontally oscillating visual target signal in either an in-phase mode or in an antiphase coordination mode. The target signal was presented on a screen in front of the participant. The figure below depicts 10 cycles of visuomotor tracking of hand (grey lines) and target (black lines) oscillations for a target frequency of 2 Hz. Minima represent flexion reversal points of the hand movements and the leftmost reversal points of the target signal.





a) Which coordination mode was performed? (**1 point**)

In-phase tracking

b) Can you infer from the data if the participant is actively coordinating his/her hand movements to a particular movement reversal point? Explain. **(3 points)**

Yes to peak flexion; lower flexion than extension endpoint variability and overall more flexed orientation. Based on these kinematic signatures, the hand is likely steered actively towards peak flexion. Another kinematic signature of anchoring is an asymmetry in peak velocity between the two half-cycles. This is not clearly visible in the presented data.

c) Draw the corresponding phase plane with normalization as applied in Computer Practical 1 and specify the normalized velocity values on the ticks of the y-axis. **(3 points)**

Circular phase planes with appropriate zero crossings at -85 and +25 degrees. Variability of flexion and extension reversal positions is different, with lower variability for flexion. Note that the amplitude is 55 degrees. Hence, normalized peak velocity should be around -55 and +55 degrees. This is the direct effect of normalization so that the phase planes have a consistent aspect ratio (scaling velocity to amplitude by dividing by 2pi omega, 'chain rule').

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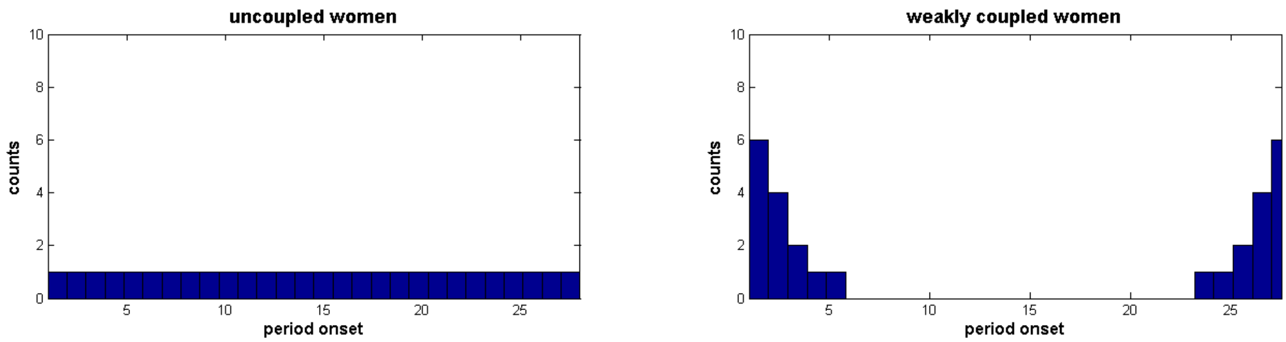
Question 5: Ensembles of weakly coupled oscillators (5 points)

Assume that 28 independent women have a regular 4 week menstrual cycle, with period onsets uniformly distributed across the sample throughout the 28 days, as depicted in the left histogram of the figure below. Then they start living together, in other words, the women become weakly coupled. Rumor has it that after a year their period onsets start to converge, as depicted in the right histogram.



a) Indicate in the Table below your rough estimates of the mean period onset day and its dispersion for uncoupled and weakly coupled women using conventional and directional statistics. **[3 points]**

	Uncoupled		**Coupled**	
	Conventional statistics	***Directional statistics***	***Conventional statistics***	***Directional statistics***
Mean	14.5	NaN	14.5	1 = 28
Dispersion	8	Infinite	12	2

b) Pattern formation and pattern change is governed by competition among different sources of information that is meaningful and specific to the pattern(s) in question. Address this competition between informational sources in the context of pattern changes observed in clapping (i.e., audience applause), as demonstrated in Lecture 1 and described in the paper by Neda et al. (2000). **[2 points]**

Two sources of information compete with each other in a rhythmic applause: 1) the clapping noise intensity to express appreciation and 2) synchronization in the clapping phases. Once the audience applauds in a synchronized mode, average noise intensity drops. This may mediate an increase in clapping rate in individual clappers in order to raise the overall noise intensity again. But this goes at the expense of a reduced coupling between the individual clappers and synchronization is likely to be lost. There is competition between clapping together and making as much noise as possible, resulting in switches between synchronized and incoherent clapping modes.

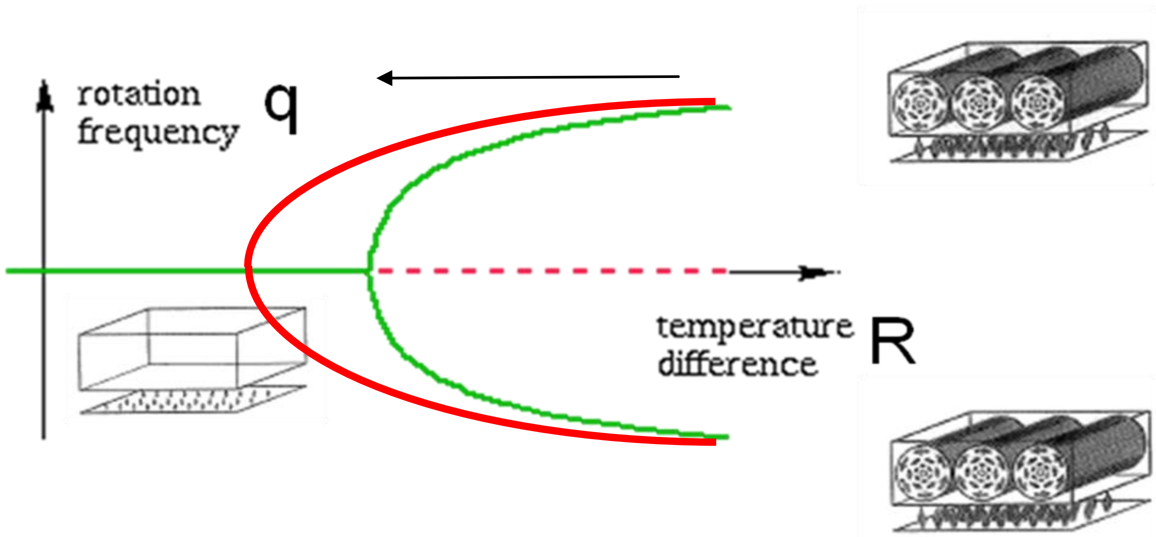
Question 6: Hysteresis (3 points)

Miura et al. (2013) studied whole-body auditory-motor coordination by letting participants bob to the beat of a metronome in either an up-on-the-beat pattern or down-on-the-beat coordination pattern. Hysteresis was a key topic in that study, which was experimentally addressed by asking participants to bob to metronomes that either increased or decreased in frequency (ascending and descending metronome conditions, respectively).

a) What was their dependent variable to quantify hysteresis? **[1 point]**

   Critical frequency

b) In the figure below, the bifurcation diagram is depicted for the Rayleigh-Bénard convection for the situation where the temperature difference R is gradually increased. Sketch in this figure the corresponding bifurcation diagram for a gradual decrease in R under the assumption that Rayleigh-Bénard convection is subject to hysteresis. **[2 points]**



Something like the red lines. Convection rolls remain visible for a lower temperature difference R.