Hold-on or Let-go

Intention and fluctuations in bimanual coordination.

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Introduction

- If my body functions as a pure mechanism according to the Laws of Nature, what is this 'I'?

E. Schrödinger, What is Life?, 1944

"What is this 'I'?". How do we get a window into this profound question? One idea (pursued here) would be to look at the difference between spontaneous events (sometimes viewed as 'unconscious') and intentional events (those that involve conscious effort). Phase transitions in bimanual coordination ([1-3]) afford a possible paradigm.

In studies of bimanual coordination, participants are told to rhythmically move their index fingers at progressively faster rates in one of two patterns, in-phase and anti-phase. The key observation [1] is that the participants generally transition from an anti-phase to an in-phase coordination pattern once the oscillation frequency crosses a (participant specific) critical value. This phase transition was deemed spontaneous or involuntary [1-3] specifically because participants were instructed, should they feel the pattern beginning to change, to let it happen. In other words, "Do not intervene" [1].

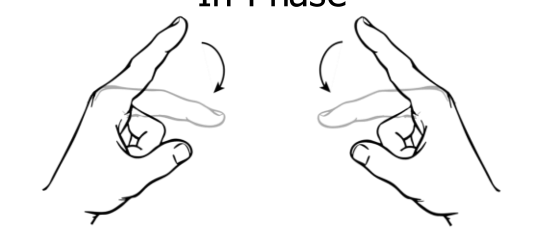
Assuming that this transition is indeed spontaneous, this experimental protocol thus exposes the body functioning as *"a pure mechanism"* . Furthermore, the mechanisms underlying this phenomenon are, from a quantitative standpoint, well understood through the Haken-Kelso-Bunz (HKB - [3]) model which characterizes the dynamics of the relative phase between the two oscillating fingers. This experimental paradigm thus offers a unique opportunity to probe the nature of intention by varying the boundary conditions in now instructing the participants, "Do intervene!".

Here, we compare the participants' behavior when instructed to Hold-on instead of Let-go to take a first quantitative step towards answering that question, *"what is this 'I'?"*

Methods

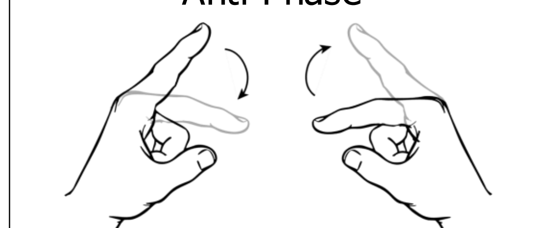
Participants are instructed to oscillate their two index fingers to the beats of a metronome. This metronome, starting at 1Hz, increases in frequency in steps of 0.25Hz every 16 cycles to reach 3.00Hz by the end of a trial. Specifically, the participants are instructed to coordinate the oscillation of their fingers in either one of two patterns: in-phase where the two fingers oscillate symmetrically of each other and anti-phase where the two fingers oscillate in parallel.

In-Phase



Symmetric movements

Anti-Phase



Parallel movements

The participants perform these coordination tasks (i.e. in-phase and anti-phase) under two conditions:

- *Let-go* : "Following the pace of the metronome, oscillate your finger in pattern *X*. Should you notice that pattern starting to change, let it happen. *Do not intervene.*"
- *Hold-on* : "Following the pace of the metronome, oscillate your finger in pattern *X*. Should you notice that pattern changing, resist that change. *Do intervene.*"

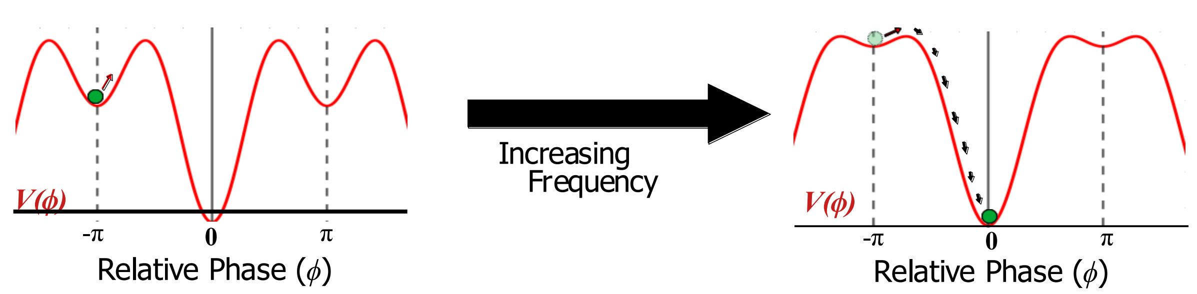
Spontaneous Phase Transitions In Bimanual Coordination

The HKB model

In the HKB model [3-5], the dynamics of the relative phase (φ), a metric of coordination) between the two index fingers corresponds to a noisy gradient descent on a potential V, the shape of this potential is determined by the ratio b/a corresponding to a control parameter that is proportional to the period of the oscillations.

$$\dot{\phi} = -\frac{\mathrm{d}V_0(\phi)}{\mathrm{d}\phi} + \sqrt{Q}\xi_t \qquad V(\phi) = a\,\sin(\phi) + b\,\sin(2\phi) + \sqrt{Q}\xi_t \qquad \langle \xi_t \rangle = 0,\ \langle \xi_t \xi_{t'} \rangle = \delta(t, t')$$

As the cycling frequency increase the potential well corresponding to anti-phase coordination shallows until fluctuations in the relative phase are enough to induce a phase transition.

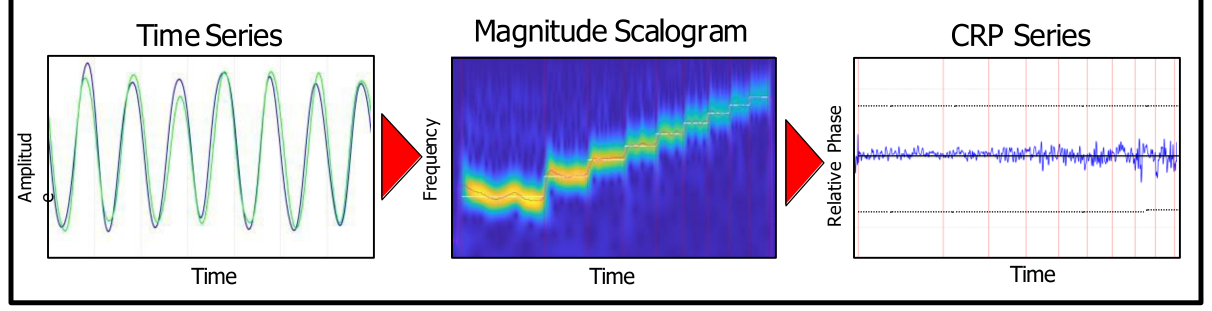


Numerous extensions of this basic model have been proposed over the years, allowing to extend its explanatory power beyond inter-limb coordination to social coordination, brain dynamics, learning and many more [5].

Results

1. Continuous Relative Phase (CRP)

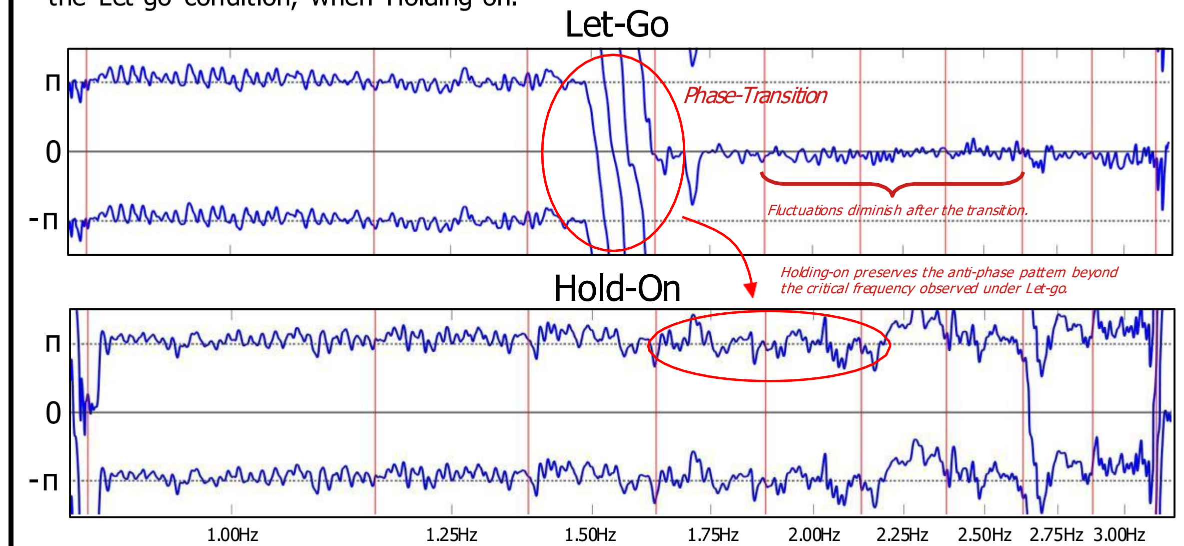
Starting from the time series generated by a participant, each finger's instantaneous phase was estimated using a Continuous Wavelet Transform. The continuous relative phase was then obtained by subtraction.



2. The Hold-on Paradox

Delayed Phase Transitions...

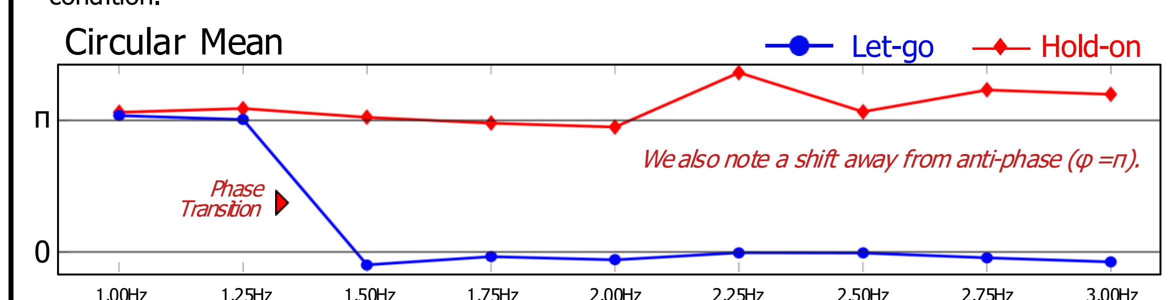
Comparing the CRP series obtained under the instruction to *Let-go* and *Hold-on* to the anti-phase pattern, it is clear that "intention" affects the CRP dynamics. First, participants are able to prevent the spontaneous transition from in-phase to anti-phase, observed in the Let-go condition, when Holding-on.

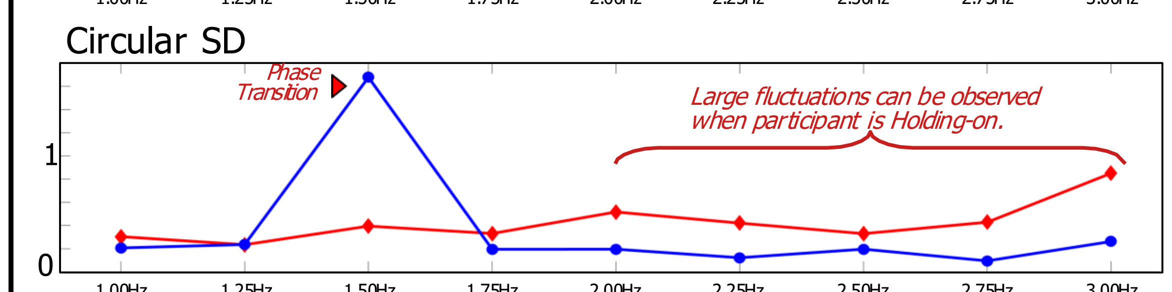


As such, we might be tempted to relate the stability of the anti-phase pattern to a measure for the "strength" of intention, as we see here that this pattern is stable for a greater range of frequencies when Holding-on.

But increased fluctuations!

This intuition is however immediately tempered by taking a look at the fluctuations in the coordination pattern when the participant is Holding-on. Indeed, the magnitude of those fluctuations (circular SD) is much greater in the Hold-on condition than in the Let-go condition.





These seemingly paradoxical observations immediately raise the following question: Are the fluctuations observed in the Hold-on condition related to the participant intention, or are they simply the result of the potential well around the anti-phase pattern becoming shallower as the frequency increases ?

3. The model perspective

To answer that question (2), we refer to an extended HKB model incorporating two additional terms :

1. Intentional Forcing Term

Previous study [6] proposed to introduce purposefulness in HKB via an intentional force:

$$V(\phi) \rightarrow V(\phi) + c\ cos(\phi - \phi_0)$$

where $c \geq 0$ is the "strength" of intention and φ_0 the desired relative phase.

2. Symmetry Breaking Term

It is known that equilibrium shifts can follow from an asymmetry in the limbs eigen-frequency [7]:

$$V(\phi) \rightarrow V(\phi) + \delta_\omega \phi$$

where δ_ω relates to the difference between the fingers' eigen-frequency.

Circular statistics as functions of the model parameters

By linearizing the model around the in-phase (φ = 0) and anti-phase (φ = π) points and solving a Fokker-Planck equation to obtain the steady state density, we can express the relative phase mean and standard deviation as functions of two aggregated parameters, k_φ and μ.

<u>Aggregated parameters:</u>

$$k_{\phi=0} = \sqrt{\frac{4b+c+a}{Q}} \qquad k_{\phi=\pi} = \sqrt{\frac{4b+c-a}{Q}} \qquad \mu = 2\delta_\omega/Q$$

Estimates of these parameters can then be obtained by matching them to the experimental values (as shown on the right).

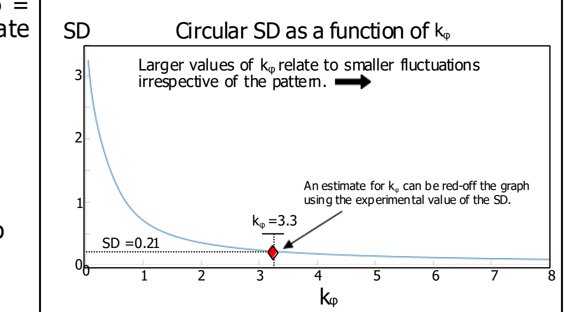
<u>Predictions</u>

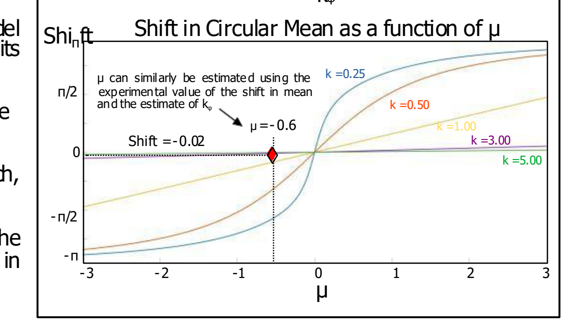
Looking at the expression of k_φ as a function of coordination pattern (φ) and model parameters (shown above) we can make the following prediction in relation to its value at each of the frequency plateau of the Let-go and Hold-on conditions.

1. Prior to the transition observed in the Let-go condition, k_φ should be greater in the Hold-on condition (c >0) than in the Let-go condition (c=0).

2. After the transition, the pattern in the Let-go condition is in-phase (φ =0). As such, the parameter a now counts positively for this condition while it counts negatively (φ =π) for the Hold-on condition. However, since the participant is able to prevent the transition by Holding-on, the parameter c should be large enough such as to drive the dynamics. In other words, k_φ should still be greater in the Hold-on condition than in the Let-go condition.

Estimation process

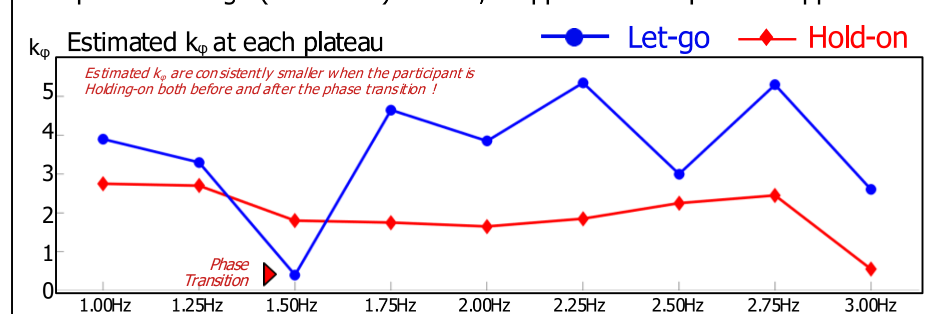


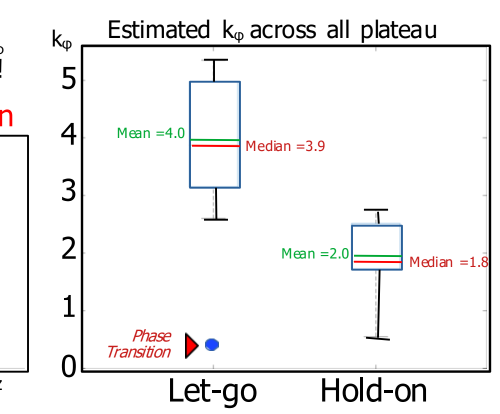


Estimated parameters across conditions:

Estimating k_φ using the measured circular SD as depicted above, we can test this prediction by comparing its value for each of the conditions at each frequency plateau.

We find that the instruction to Hold-on does not increase the value of k_φ compared to Let-go (see below). In fact, it appears to be quite the opposite !





According to the model the only way k can be smaller in the Hold-on condition is if Q increases. But in all stochastic modeling of bimanual coordination, whether intentional or not [1-5], Q, the noise level, is fixed. Our results suggest, however, that the intention to Hold-on is tied to the magnitude of noise.

Conclusion & Future Investigations

<u>Our results show that:</u>

1. Intention to Hold-on to anti-phase coordination delays the transition to in-phase.
2. This is not without consequences. Relative to the in-phase pattern, over the same parameter range, intention to Hold-on comes with a significant increase in fluctuations.
3. Modeling predicts that this cannot happen unless the magnitude of fluctuations, Q, varies as a function of intention.

This suggests that the nature of Schrödinger's *'I'* is both deterministic and stochastic.

Follow-up investigations, both empirical and theoretical, are underway to characterize the relationship between intentionality and fluctuations (*e.g.,* in the context of social interactions).

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