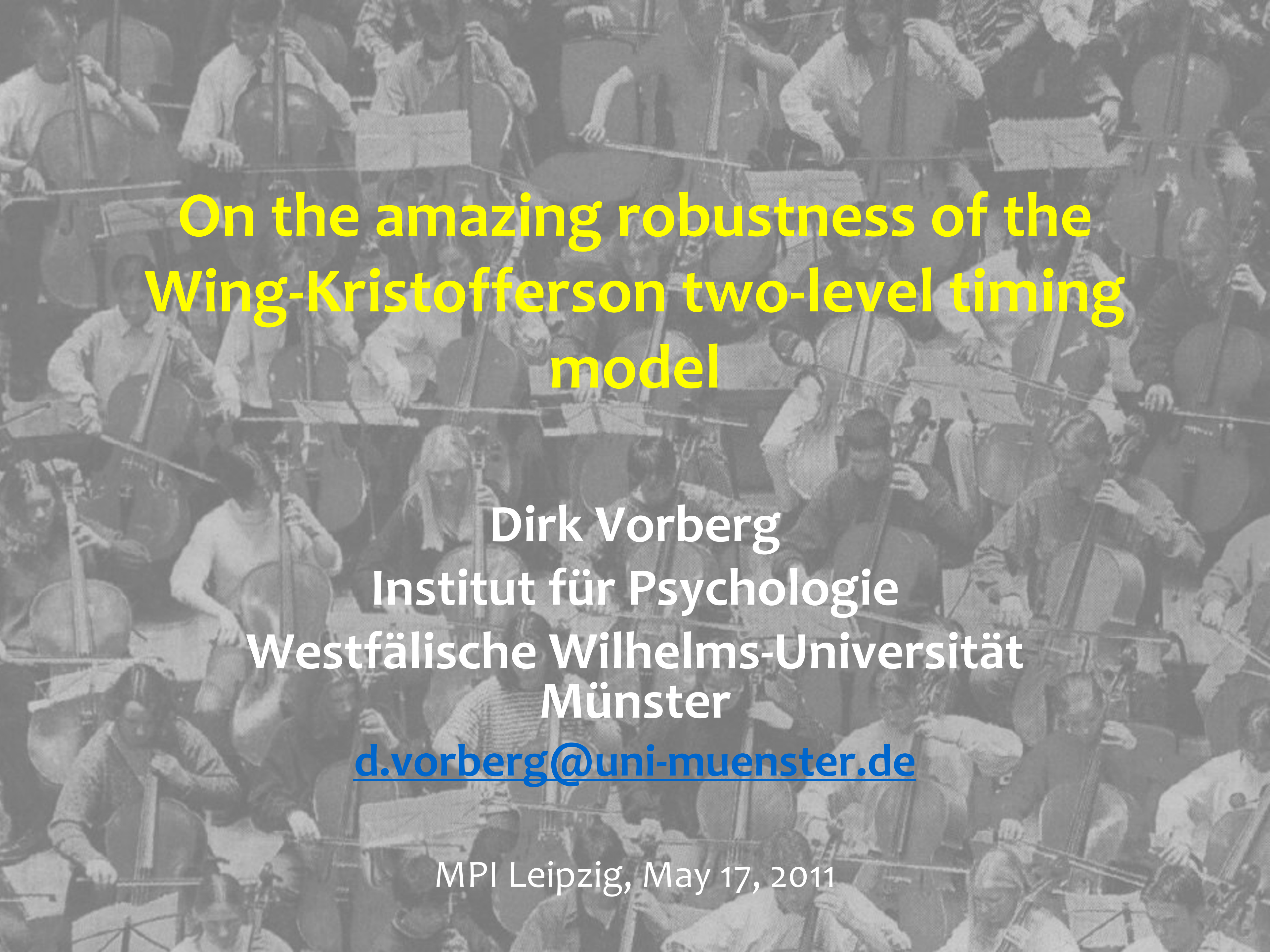
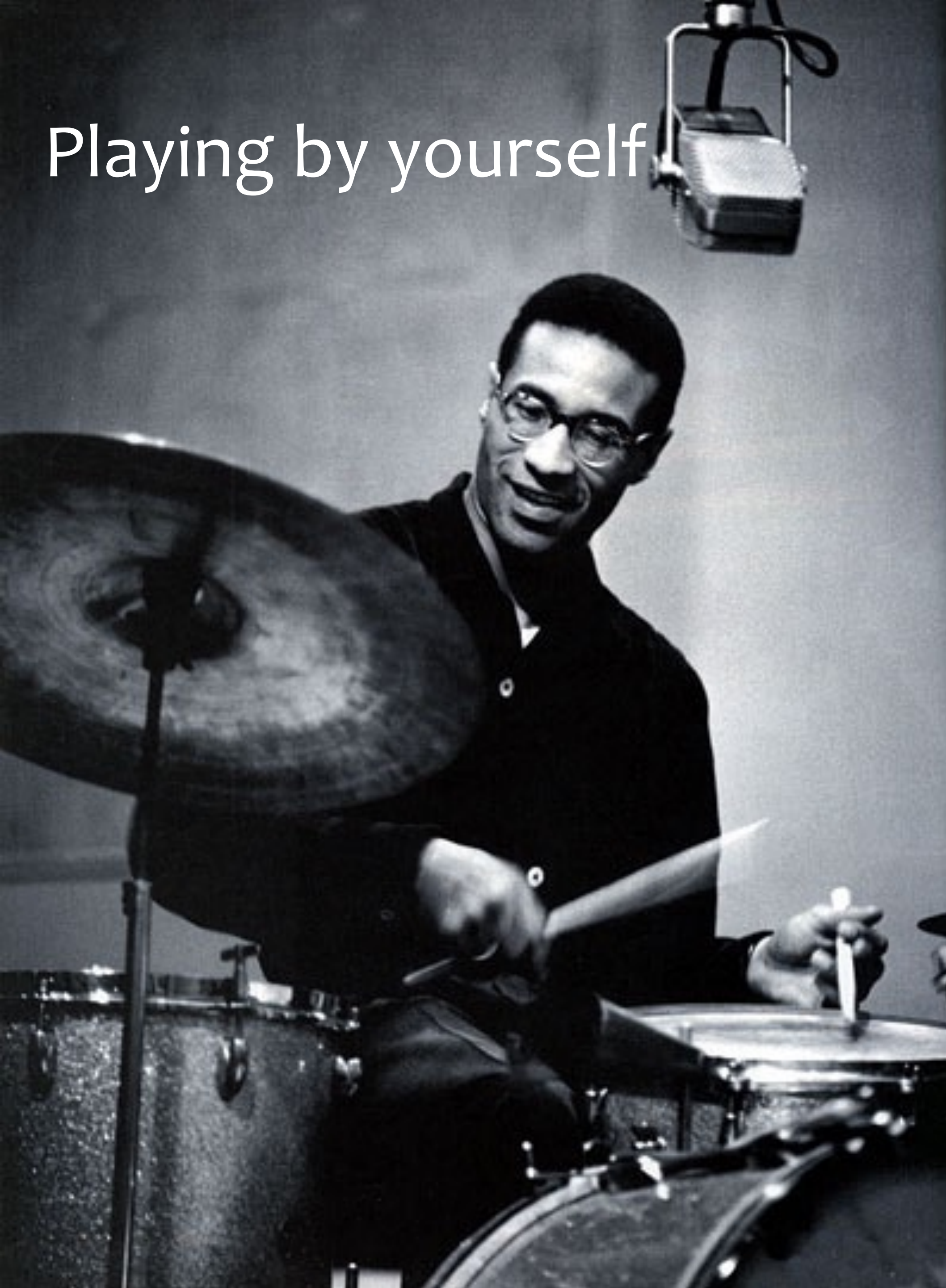


On the amazing robustness of the Wing-Kristofferson two-level timing model

Dirk Vorberg
Institut für Psychologie
Westfälische Wilhelms-Universität Münster
d.vorberg@uni-muenster.de

MPI Leipzig, May 17, 2011

Playing by yourself



Ensemble Playing: Synchronizing without a leader (?)

Following (?) the conductor

Amazingly perfect synchronization –

– well, not always

(traditional Cambrigde–Oxford boat race)

Overview

1 The Wing-Kristofferson Two-Level model of temporal control

- Empirical findings and applications
- Extensions of the model to musical rhythms

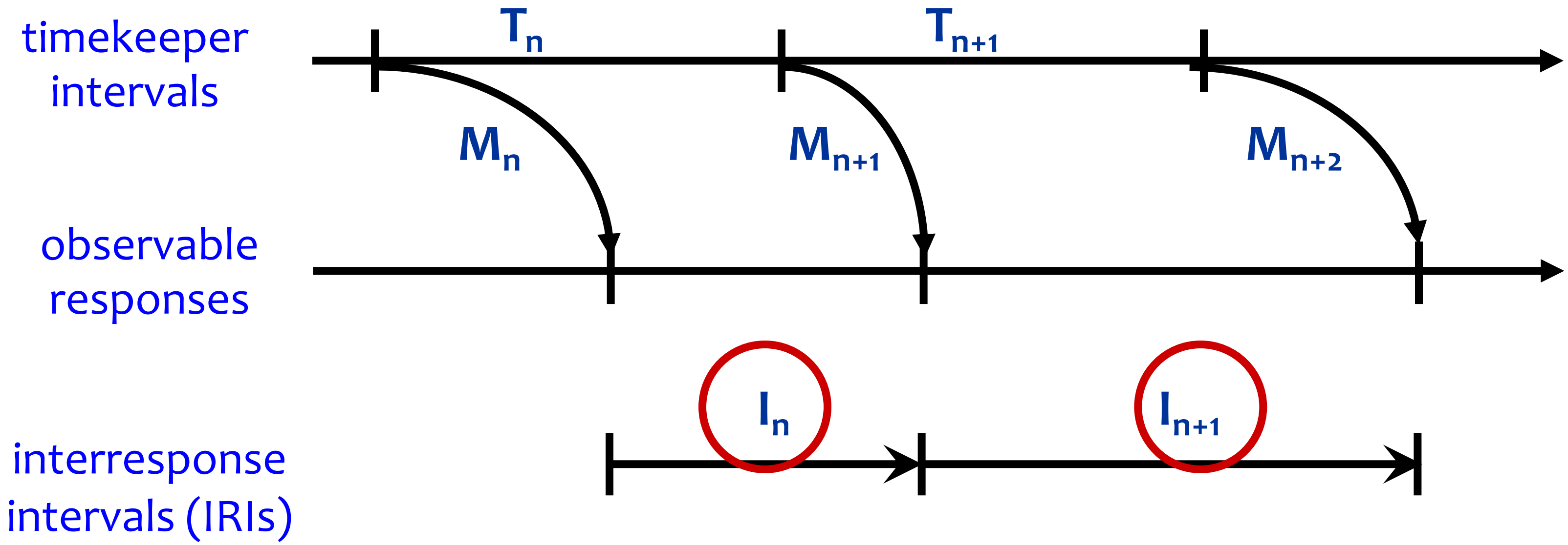
2 Why is the basic model so successful?

- Problematic findings
- An extended two-level model

The Two-Level model: Assumptions

A Wing & AB Kristofferson (1973), *Perception & Psychophysics*, **14**, 5-12.

Alan Wing



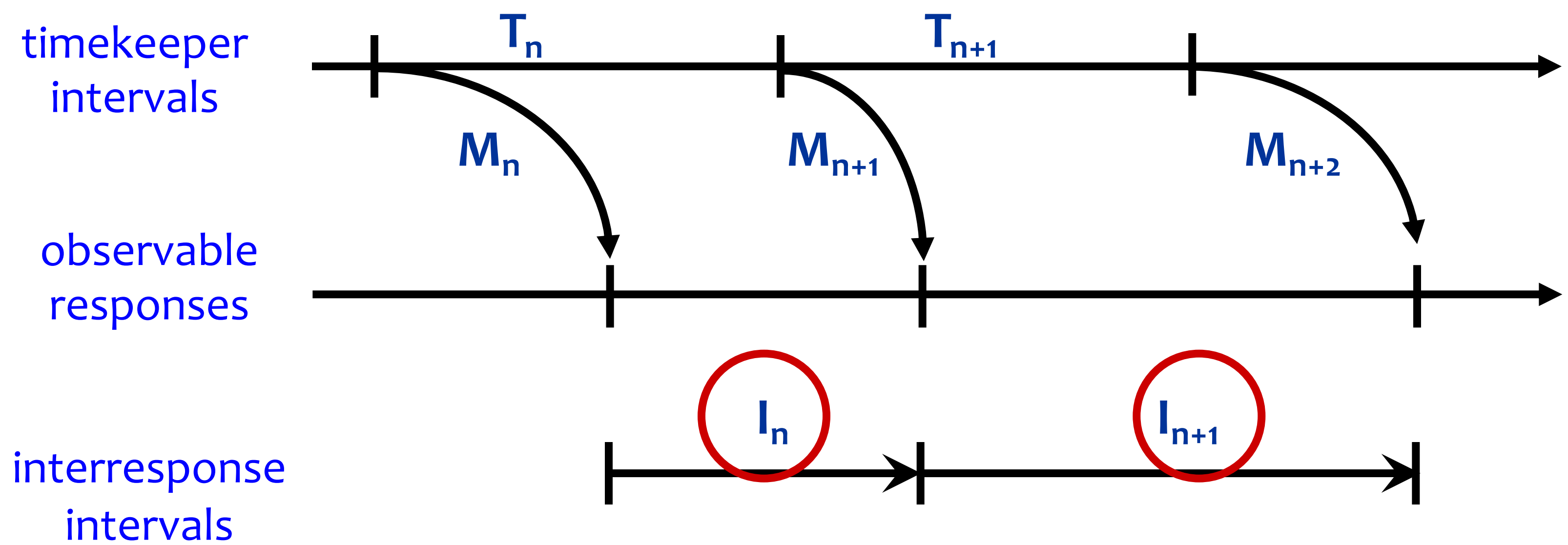
Assumptions:

The timekeeper $\{T_n\}$ and motor delay $\{M_n\}$ random variables are

1. *stochastically independent* of each other and
2. *stationary*, i.e., have constant means and variances.

The Two-Level model: Predictions

A Wing & AB Kristofferson (1973), *Perception & Psychophysics*, **14**, 5-12



$$I_n = T_n + M_{n+1} - M_n$$

predicted auto-covariance function (acvf)

$$\mathrm{var}(I_n) = \mathrm{var}(T) + 2\mathrm{var}(M)$$

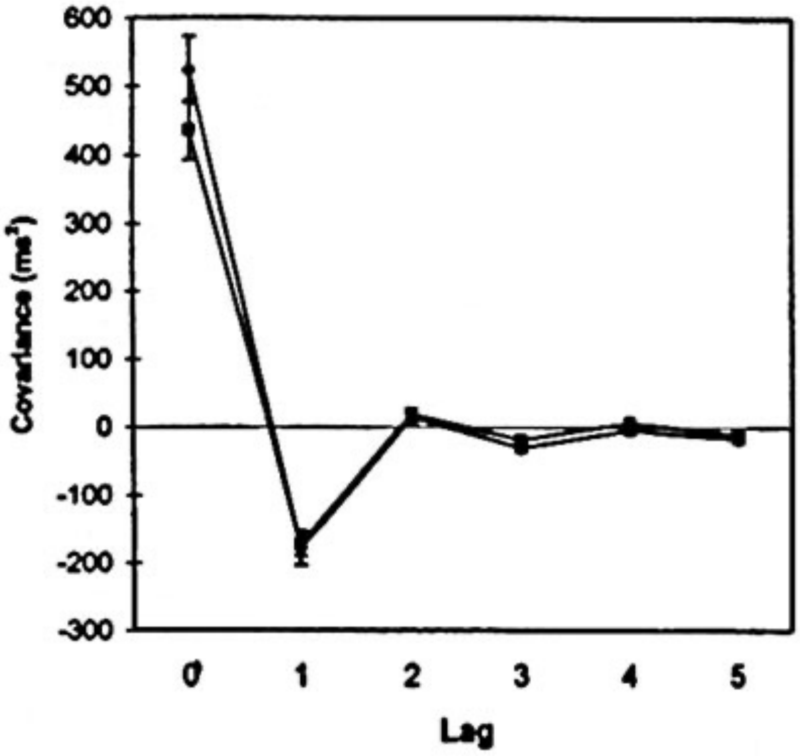
$$\mathrm{cov}(I_n, I_{n+k}) = -\mathrm{var}(M) \qquad k=1$$

$$= 0 \qquad k>1$$

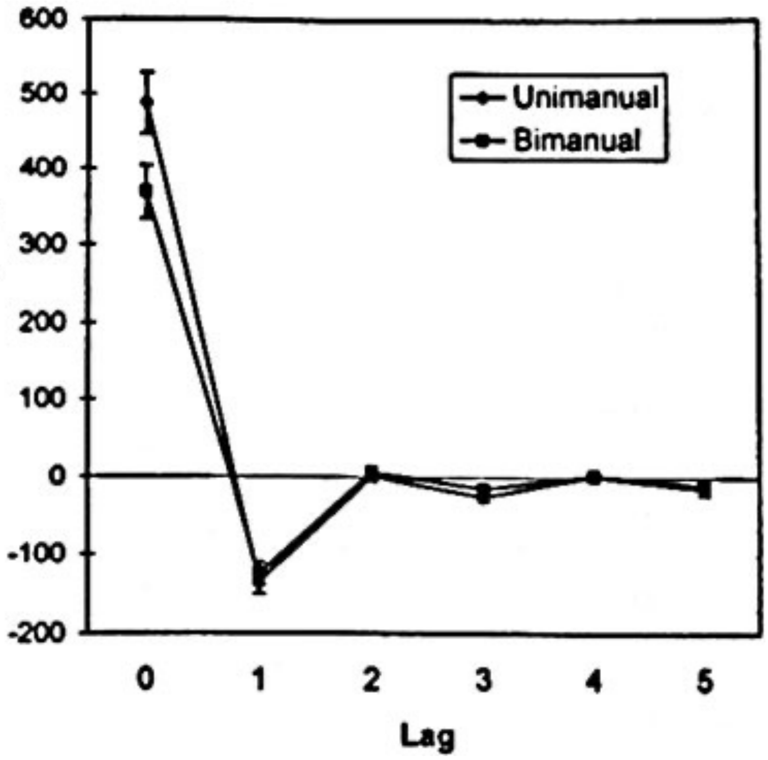
Empirical acvf for uni-manual and bi-manual finger tapping

LL Helmuth & RB Ivry (1996), *JJEP:HPP*, **22**, 278-293.

left hand

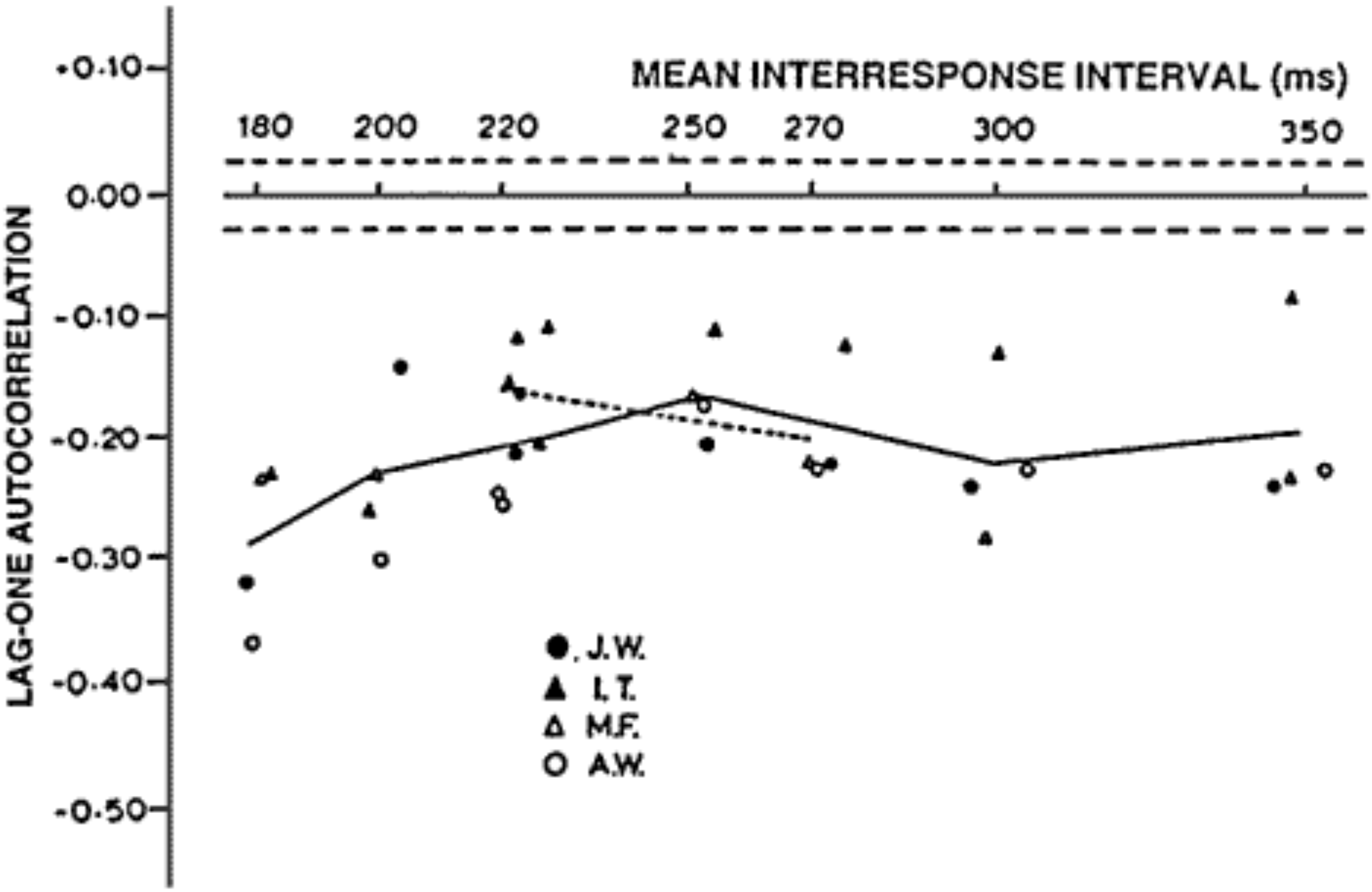


right hand



Negative lag-1 dependence in continuation tapping

(A Wing, 1973)



Important properties of two-level model

Testability:

→ predicted shape of the *acvf*

Decomposability of observed variability into two sources:

→time-keeper variability (central)

→ implementation variability (peripheral)

What limits timing precision?
Separating central from peripheral sources of variance

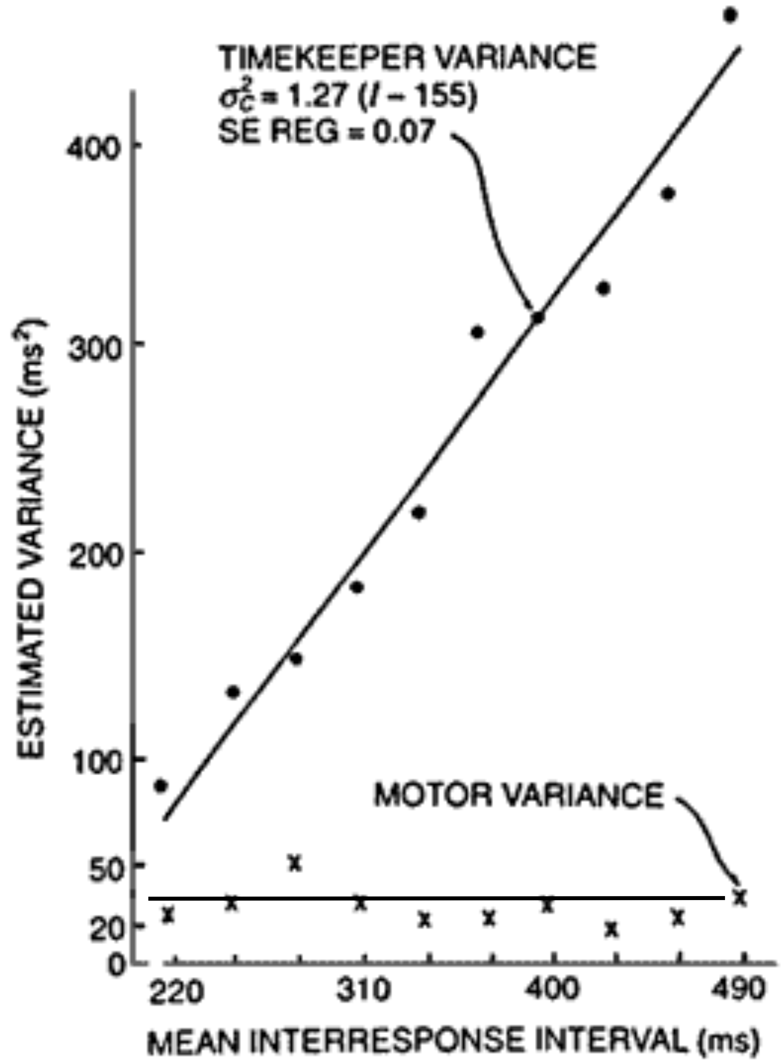
From

$$c(0) = var(I_n) = var(T) + 2var(M)$$
$$c(1) = cov(I_n, I_{n+1}) = - var(M)$$

we get

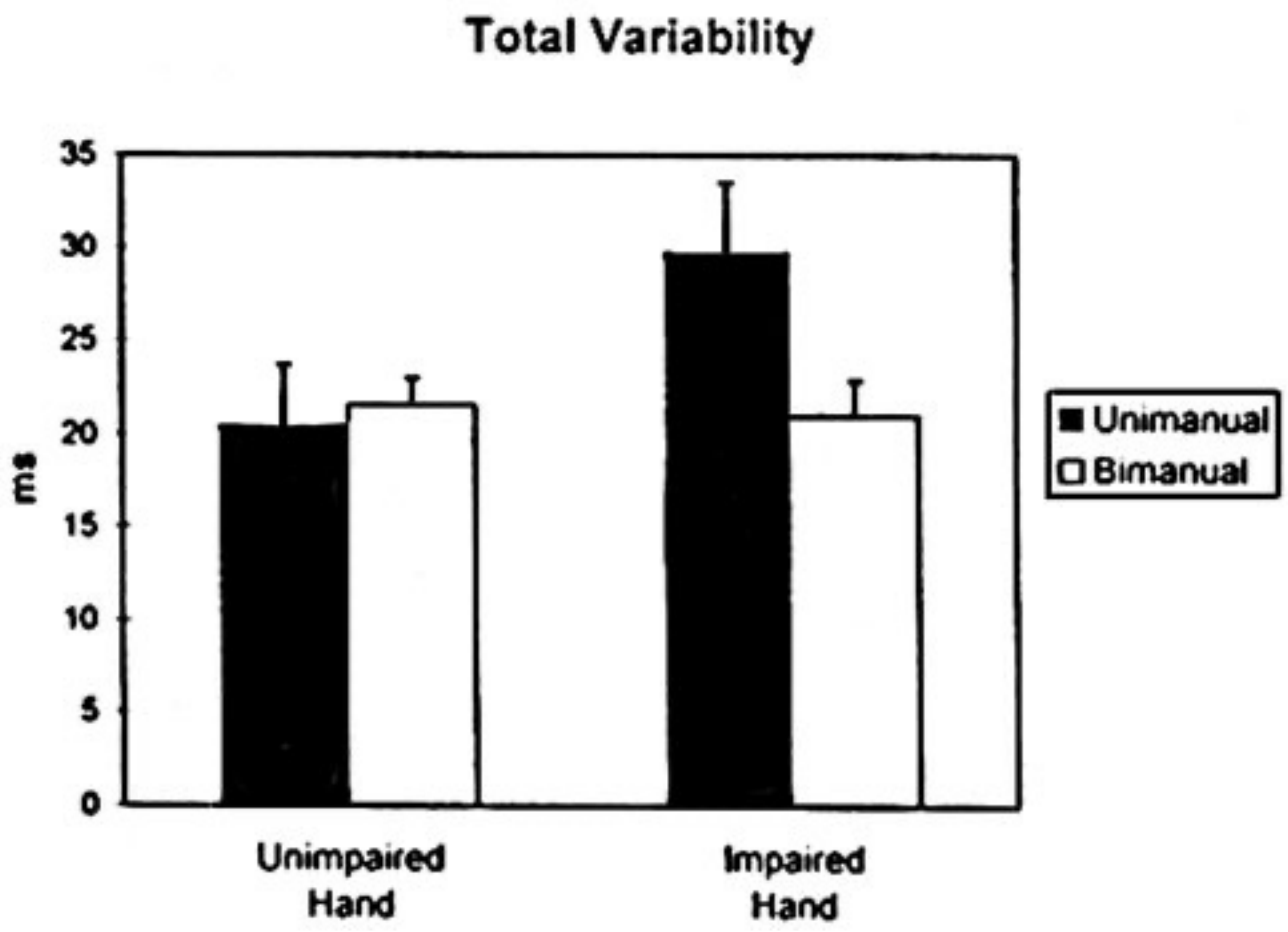
$$var(T) \leftarrow c(0)+2c(1)$$
$$var(M) \leftarrow - c(1)$$

Dissociating timekeeper and motor delay variances: Parameter estimates (Wing, 1973)



Uni- and bimanual tapping by patients with cerebellar lesions

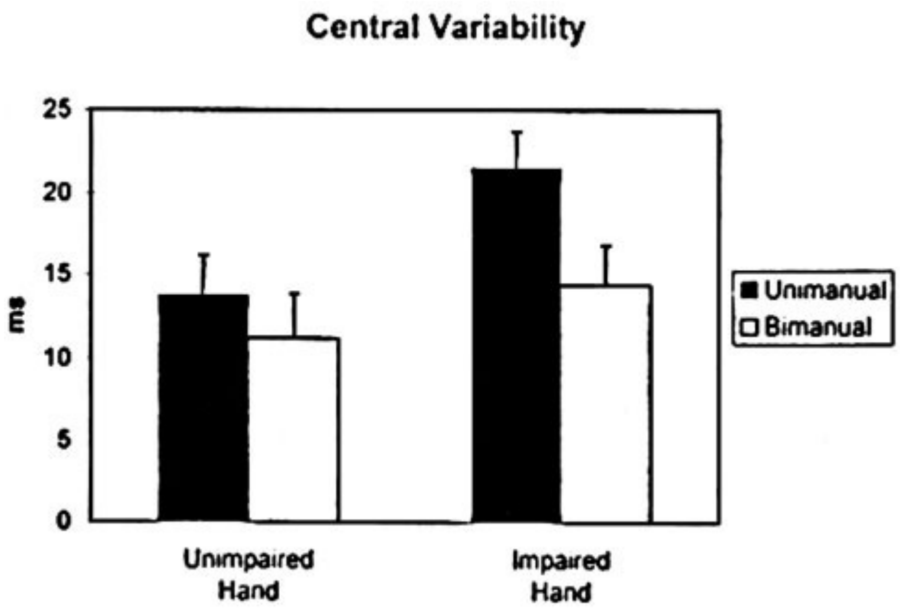
EA Franz, RB Ivry & LL Helmuth (1996), *Journal of Cognitive Neuroscience*, **8**, 107-118.

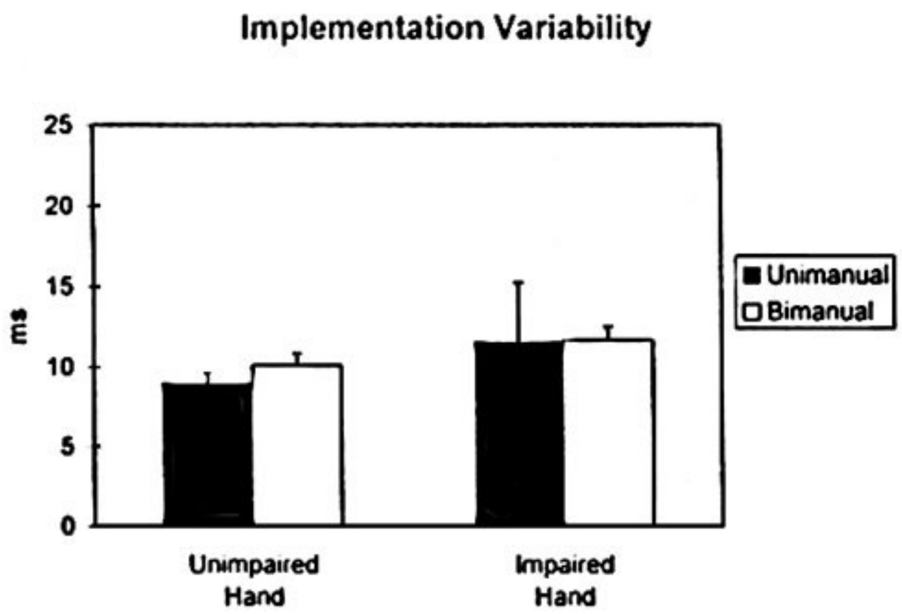


Uni- and bimanual tapping by patients with cerebellar lesions

Franz, Ivry & Helmuth (1996)

Variance decomposition into central and peripheral sources





Pitfalls in testing and rejecting valid models

Several tests reported in the literature seem to have falsified the WK two-level timing model.

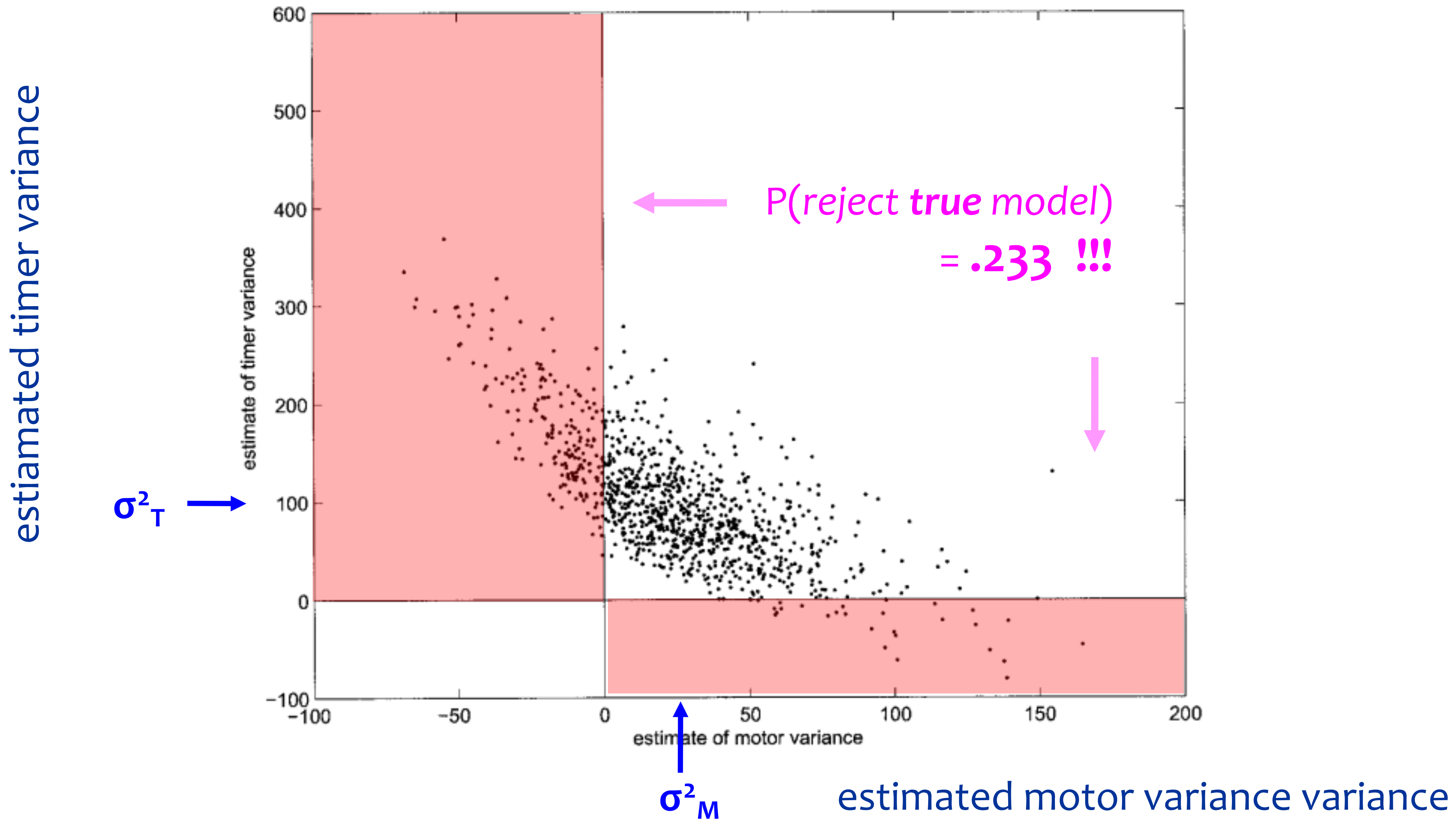
However, important caveats are often ignored:

- Non-stationarity (e.g., drifts, usually due to long sequences) distorts the shape of the acvf.
- Tests of probabilistic predictions should not ignore statistics!

Monte-Carlo simulation of the WK continuation model

D Vorberg & HH Schulze (2002), *JMP*, **46**, 56-87.

Scatter plot of bias-corrected **parameter estimate pairs** from **1000 sequences of 30 IRIs each,** generated by model with var(M)=25 and var(T)=100.



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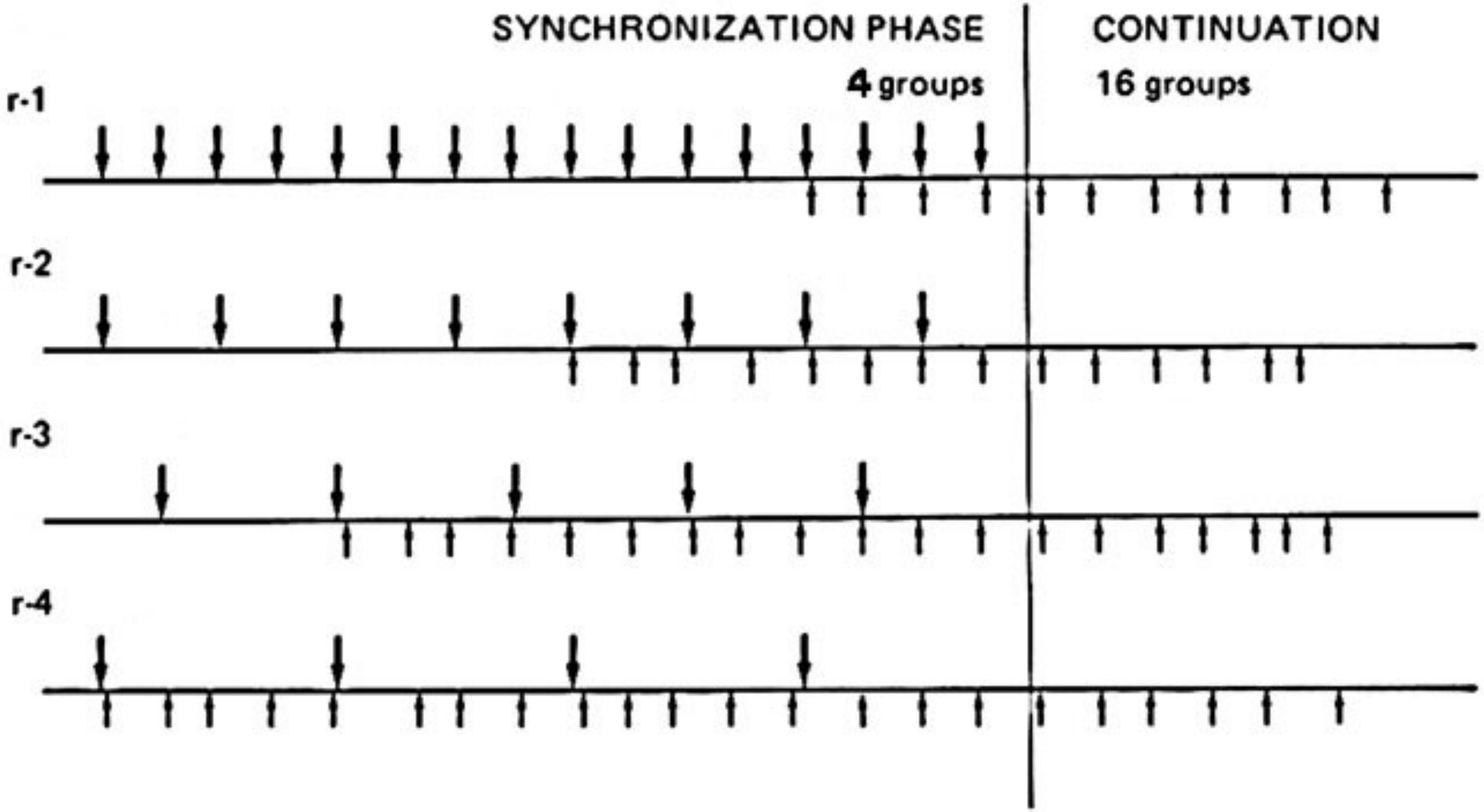
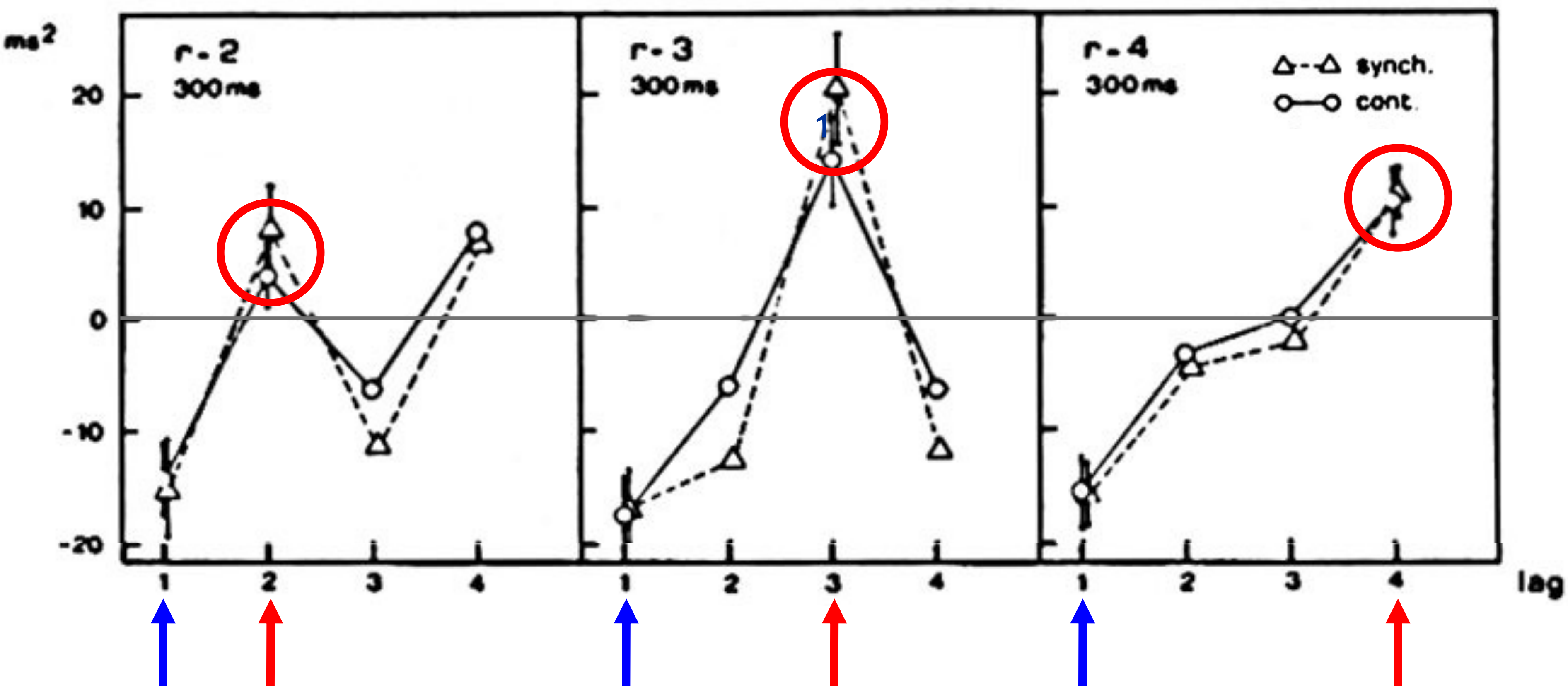
Rolf Hambuch

Extensions
Hierarchical or sequential control in grouped tapping
D Vorberg & R Hambuch (1978), *Attention & Performance* VII, 535-555



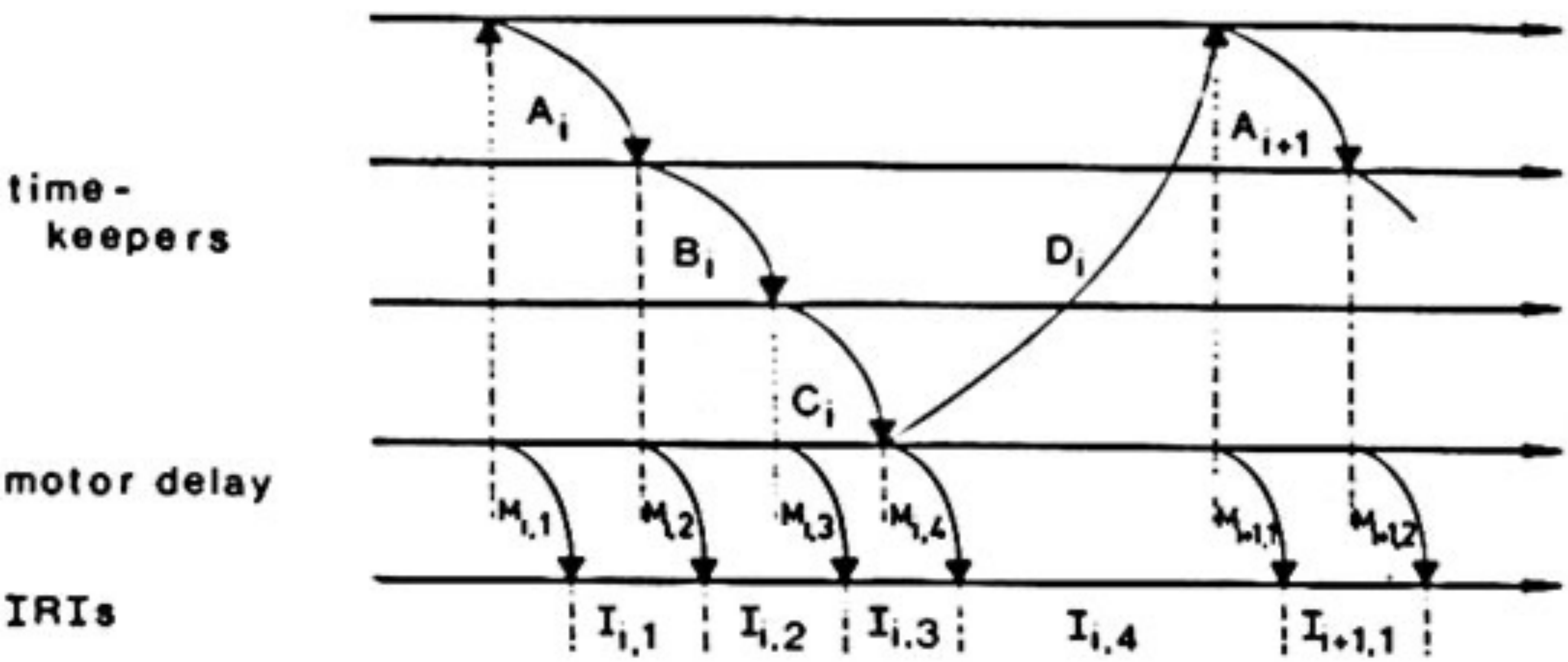
Empirical acvfs in grouped continuation tapping

D Vorberg & R Hambuch (1978), *Attention & Performance* VII, 535-555

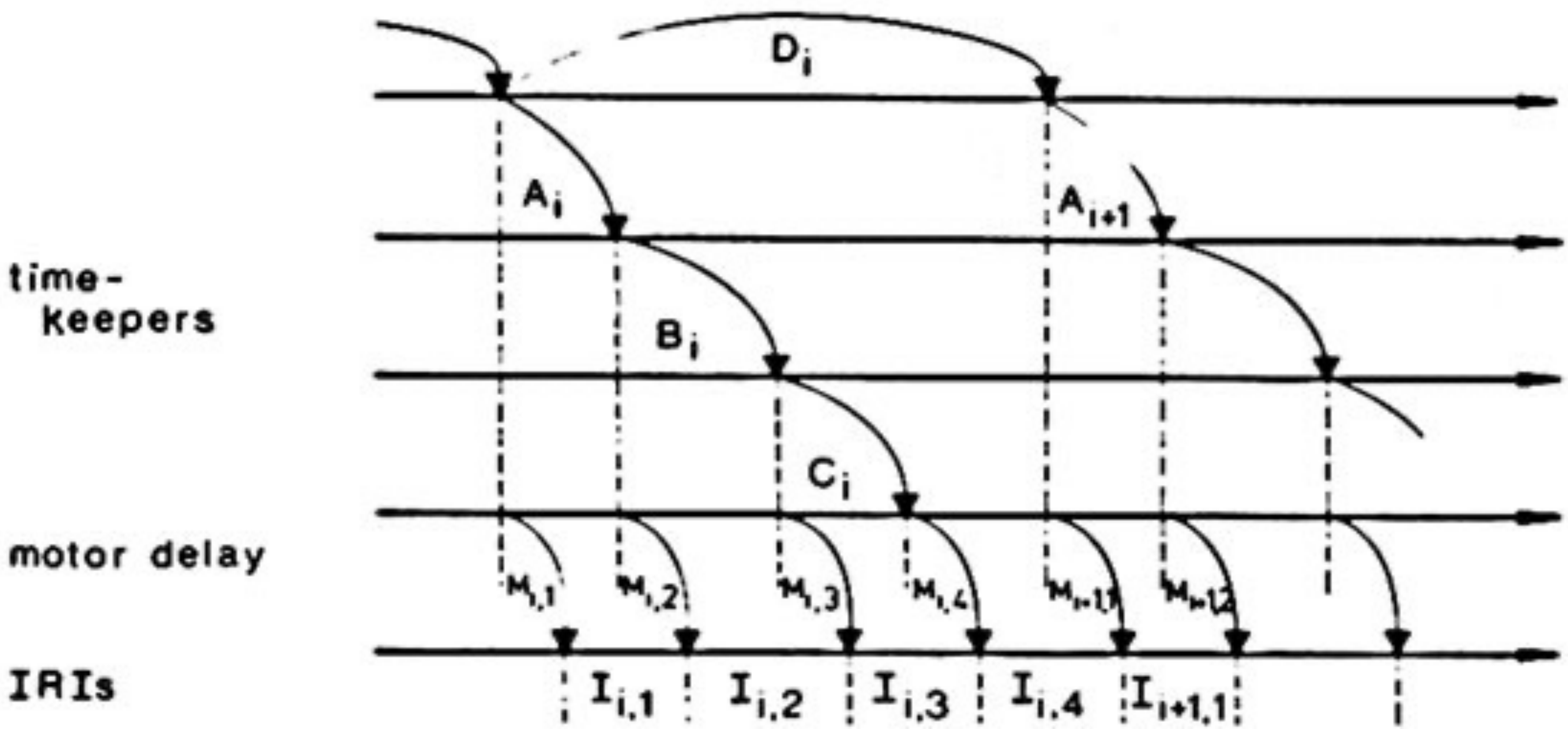


alternative models for grouped tapping

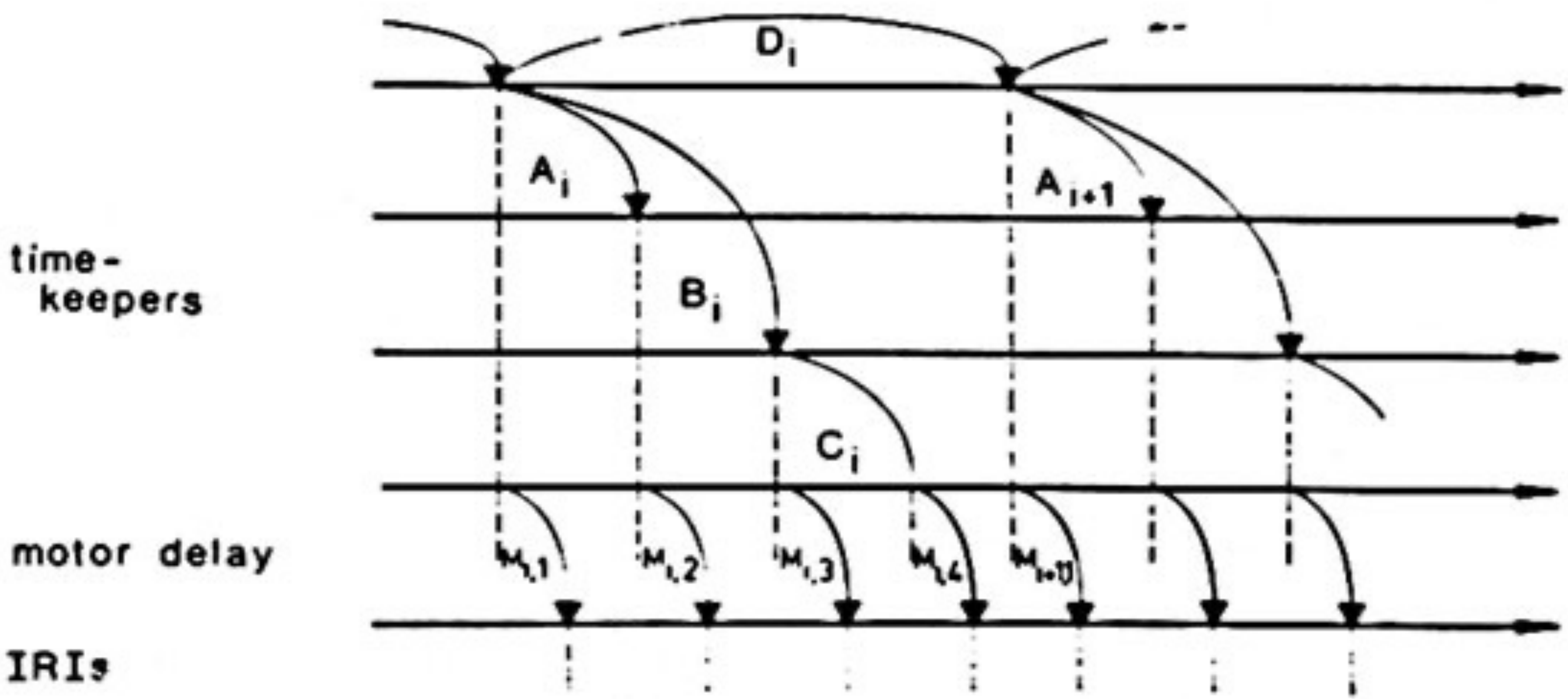
model I: sequential chain of timekeepers



alternative models for grouped tapping
model II: superordinate timing + sequential



alternative models for grouped tapping
model III: fully hierarchical timing



How can we distinguish the model alternatives from each other?

→ Predicted dependency structure within measures

D Vorberg & R Hambuch (1978), *Attention & Performance* VII, 535-555

Model I

	$I_{i,1}$	$I_{i,2}$	$I_{i,3}$	$I_{i,4}$
$I_{i,1}$	$a + 2m$	$-m$	0	0
$I_{i,2}$		$b + 2m$	$-m$	0
$I_{i,3}$			$c + 2m$	$-m$
$I_{i,4}$				$d + 2m$

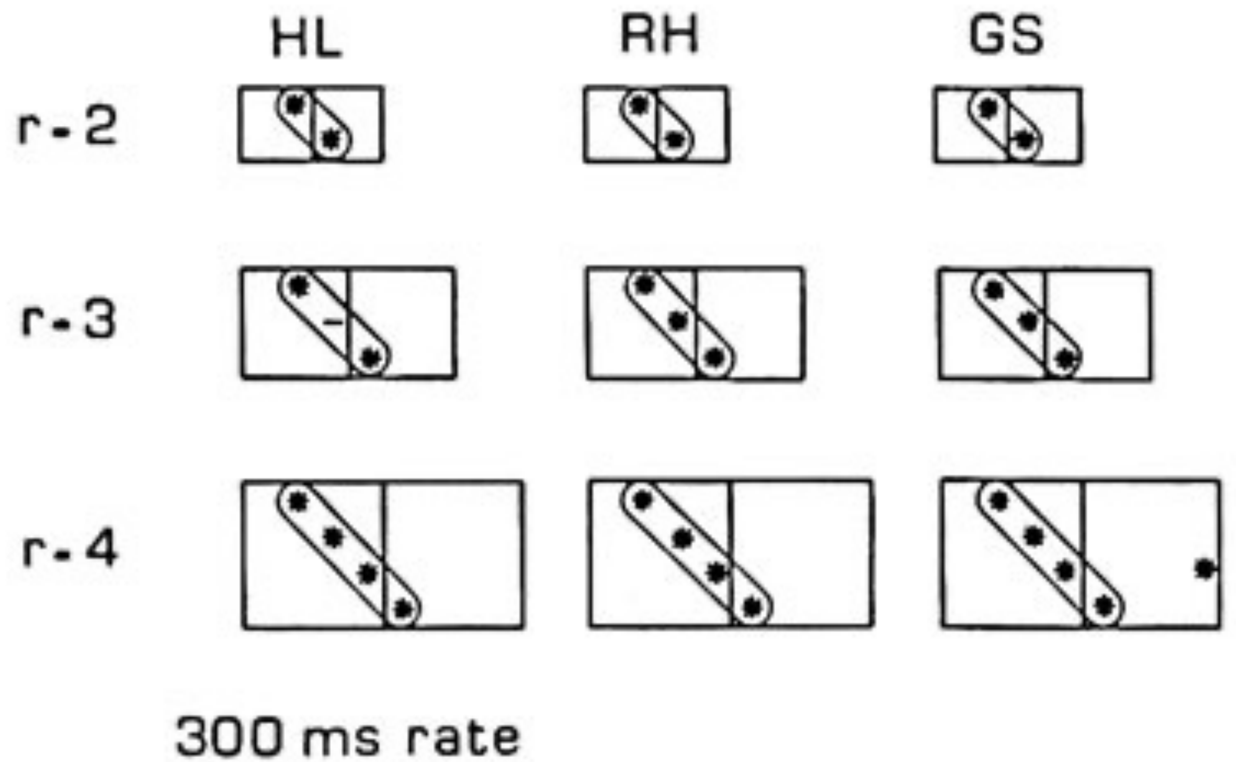
Model II

	$I_{i,1}$	$I_{i,2}$	$I_{i,3}$	$I_{i,4}$
$I_{i,1}$	$a + 2m$	$-m$	0	$-a$
$I_{i,2}$		$b + 2m$	$-m$	$-b$
$I_{i,3}$			$c + 2m$	$-c-m$
$I_{i,4}$				$a + b + c + d + 2m$

Model III

	$I_{i,1}$	$I_{i,2}$	$I_{i,3}$	$I_{i,4}$
$I_{i,1}$	$a + 2m$	$-a-m$	0	0
$I_{i,2}$		$a + b + 2m$	$-m$	$-b$
$I_{i,3}$			$c + 2m$	$-c-m$
$I_{i,4}$				$b + c + d + 2m$

Observed variance-covariance-matrices of time intervals within and between successive measures (*: r<0, p=.05)



These findings

- argue against fully or partly hierarchical timekeepers
- support the sequential chain model only

Vorberg & Hambuch (1978)

Further extensions and successful tests of the model


Ralf Krampe

Bimanual tapping

- dotted rhythms (e.g., 3-1-2-2, 1-3-2-2)

  Vorberg & Hambuch, *Proc NYAS*, 1984

- polyrhythms (e.g., 3 against 2, 4 against 3)

  Krampe, Kliegl, Engbert, Mayr & Vorberg, *JEP:HPP*, 2000

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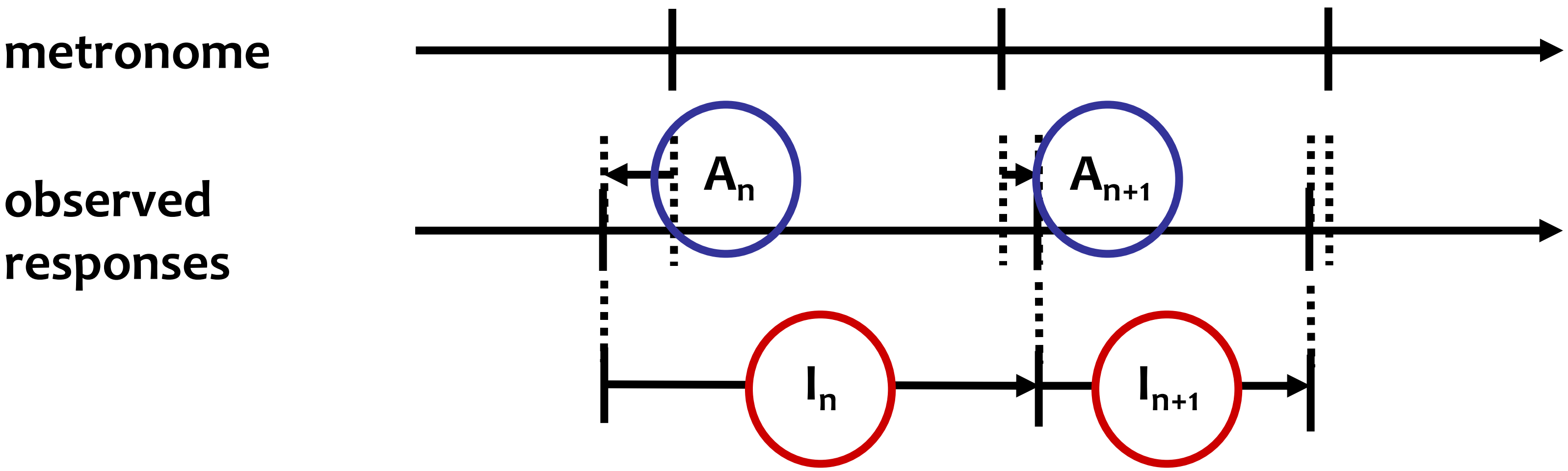
Task: Tap in close synchrony with metronome

data:

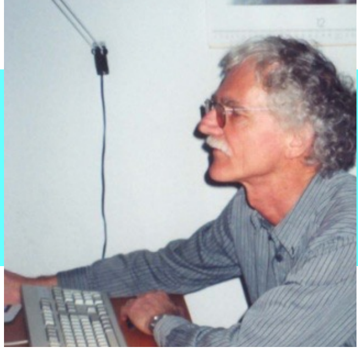
inter-response intervals, $\mathbf{I}_n$

signed deviation from metronome (‚asynchronies‘), $\mathbf{A}_n$

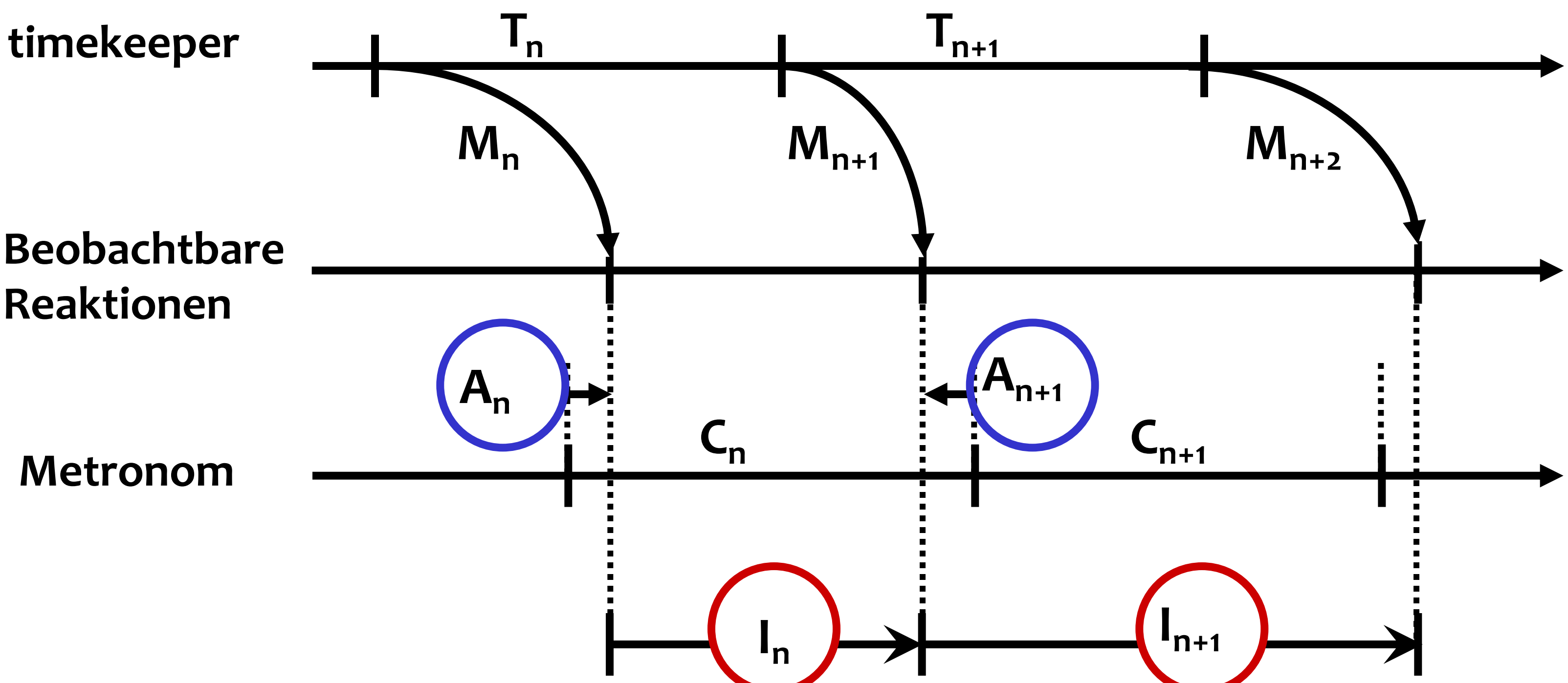


Two-level model for synchronized tapping

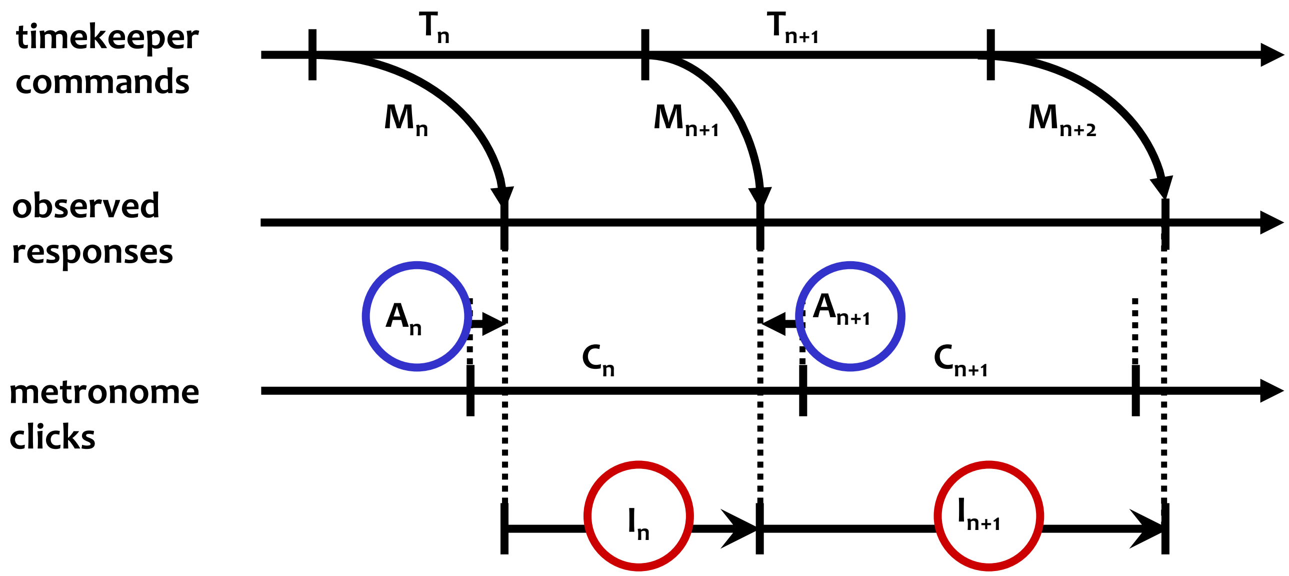
D Vorberg & A Wing (1994, 1996), D Vorberg & HH Schulze (2002), *JMP*, **46**, 56-87.



Hans-Henning Schulze



Problems for the two-level model



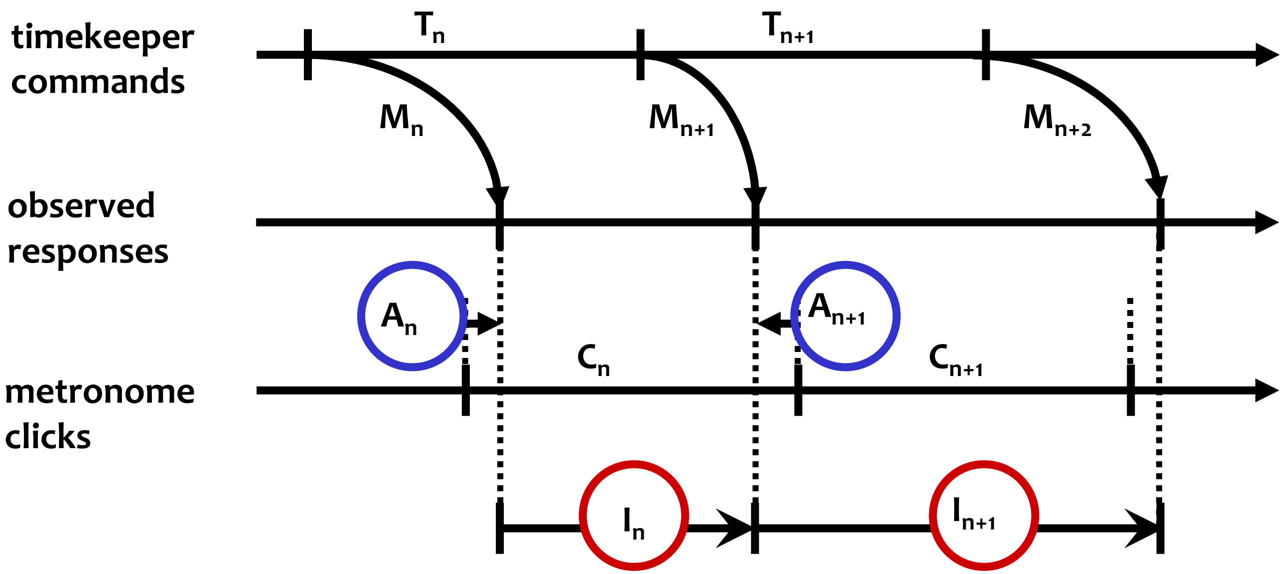
If timekeeper var(T) > 0 , performance will run out of synch - *unless deviations from metronome clicks are corrected for!*

Two-level models without an error correction mechanism *cannot* handle synchronisation performance.

→ Extending the model: Add linear *feedback-loop*!

A phase-correction two-level model

Vorberg & Wing (1996), Vorberg & Schulze, *Journal of Mathematical Psychology*, 2001, **46**, 56-87. Schulze & Vorberg, *Brain & Cognition*, 2002, **48**, 80-97



Basic assumption:

$$T_n^* = T_n - \alpha A_n$$

Testable recursion for asynchrony timeseries:

$$A_{n+1} = (1- \alpha)A_n + (T_n+M_{n+1}-M_n) - C_n$$

Note that metronome need not be perfect, i.e., $\mathrm{var}(C_n) > 0$

How can we test the synchronisation model?

Andras Semjen

→ derive and fit model predictions to synchronisation data

estimate parameters

evaluate goodness-of-fit

→ Semjen, Schulze & Vorberg (2000) *Psychological Research* **63**, 137-147

succsessful fit of two-level model, simultaneously to continuation and synchronsation performance

→ study response to experimental perturbations of metronome

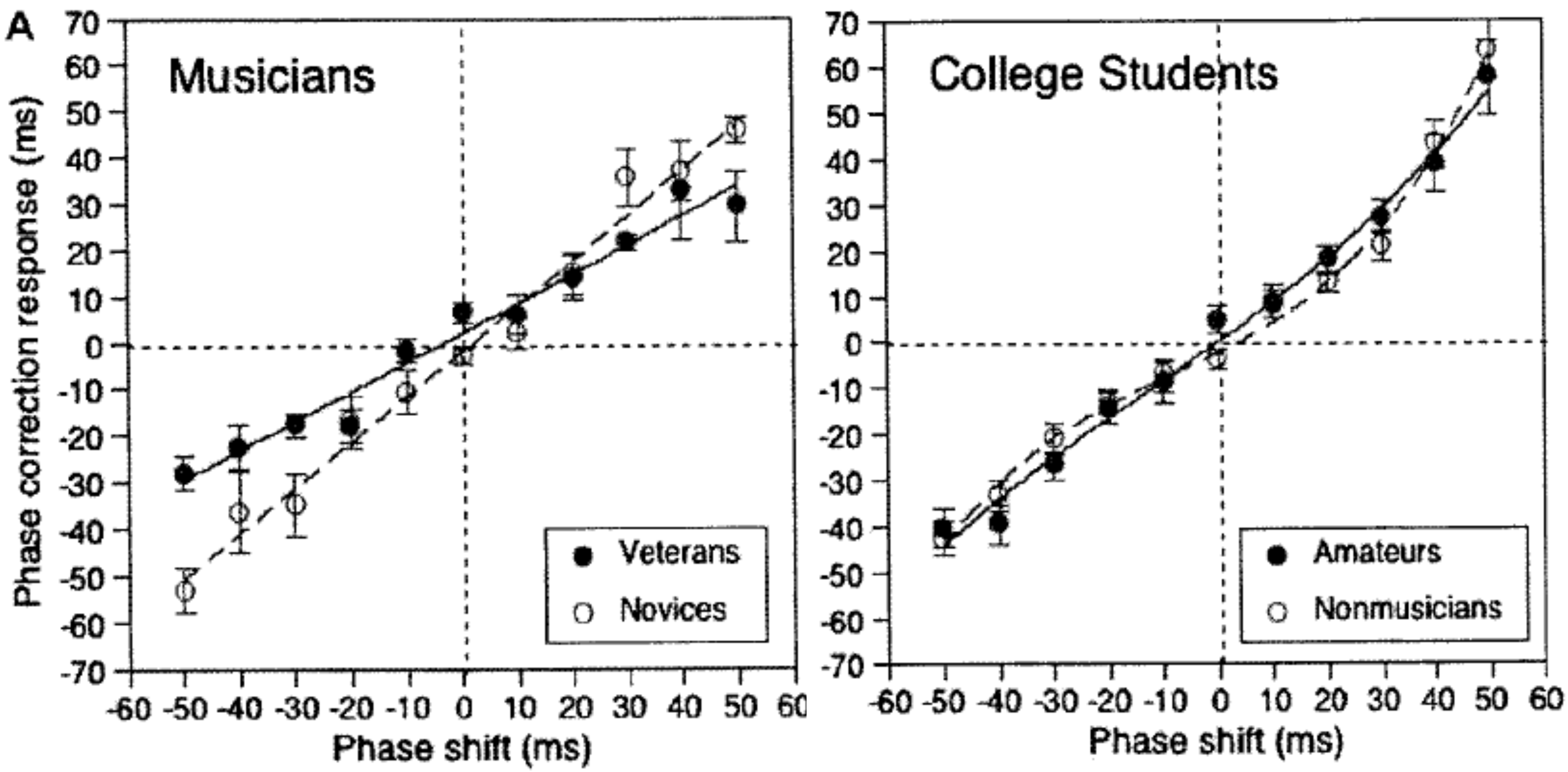
direct test of linearity assumption

→ Repp (2010), *Human Movement Science*, **29**, 200-213

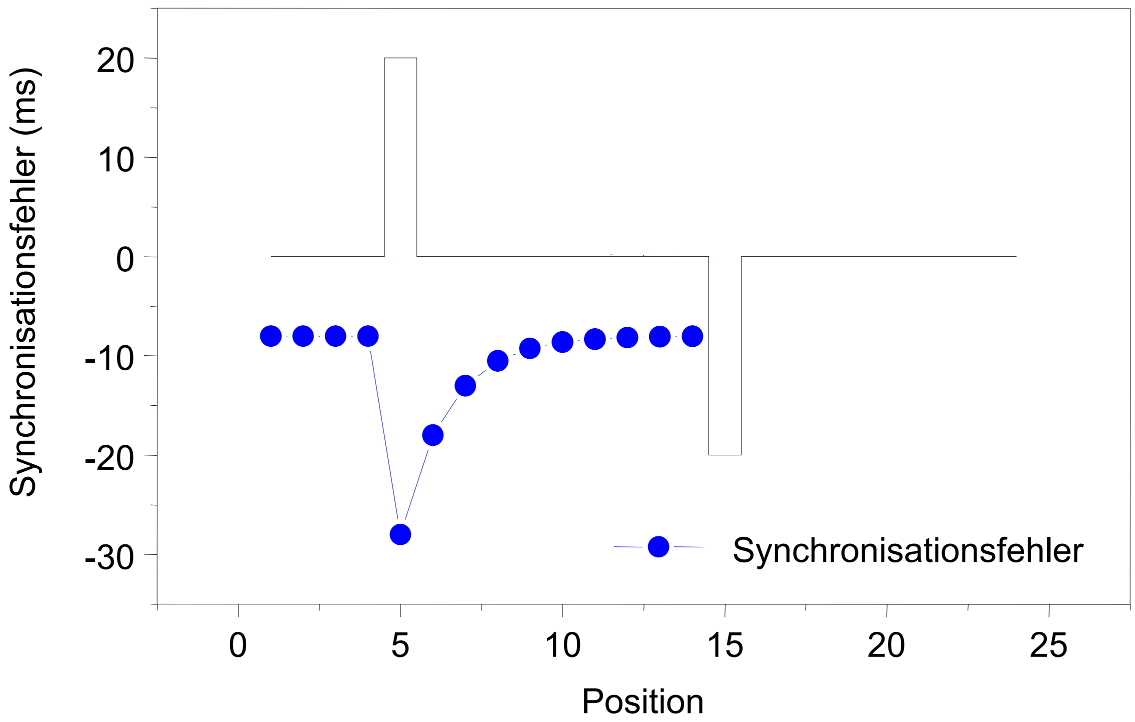
→ Fuchs (2006), Doctoral Thesis, TUBS

Mean response to single phase shifts in a regular metronome

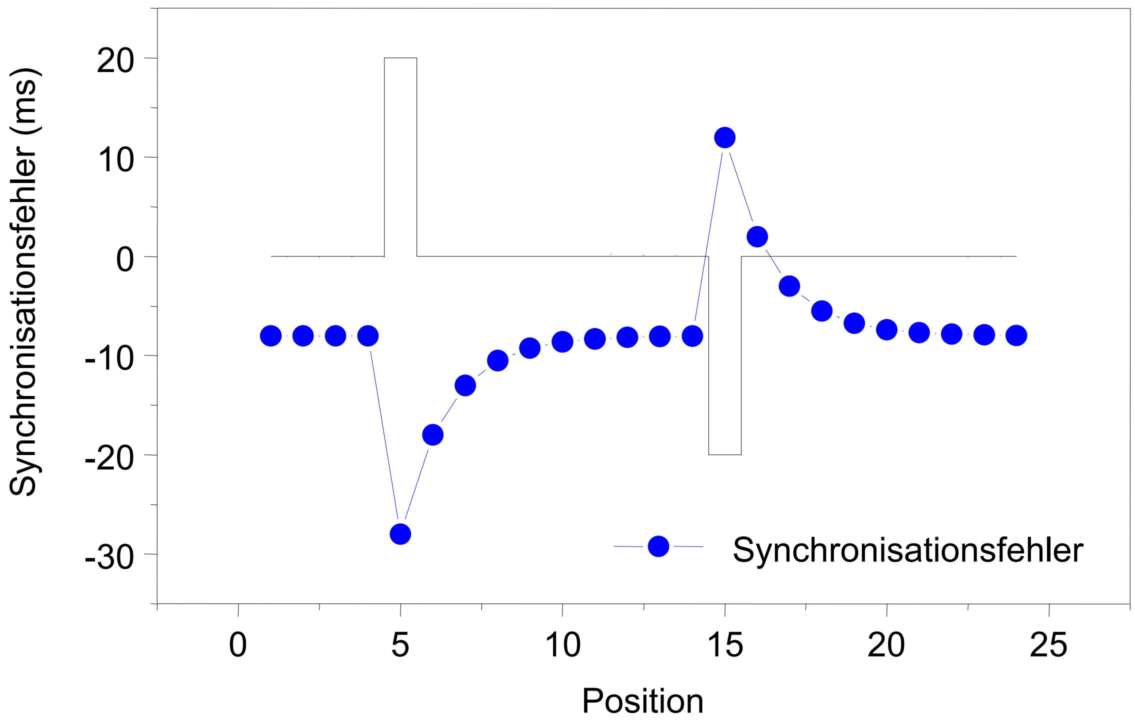
B Repp (2010), *Human Movement Science*, **29**, 200-213



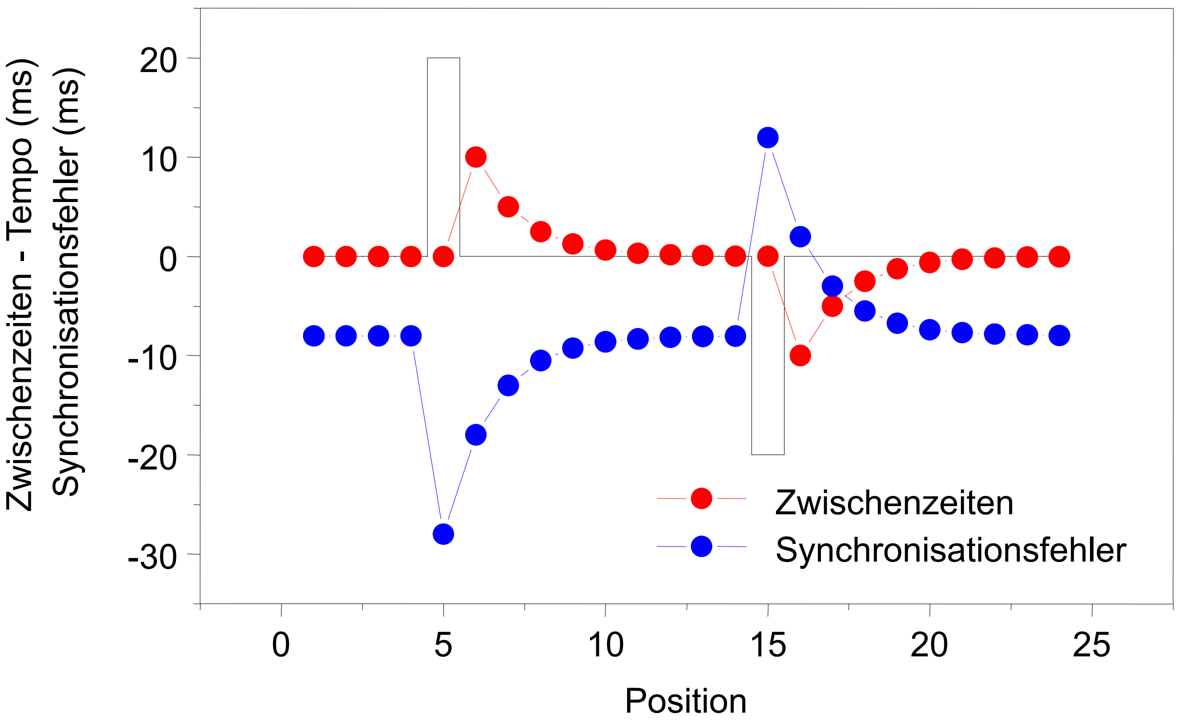
Response of the model to single perturbations: Effects on asynchronies and interresponse time



Response of the model to single perturbations: Effects on asynchronies and interresponse time

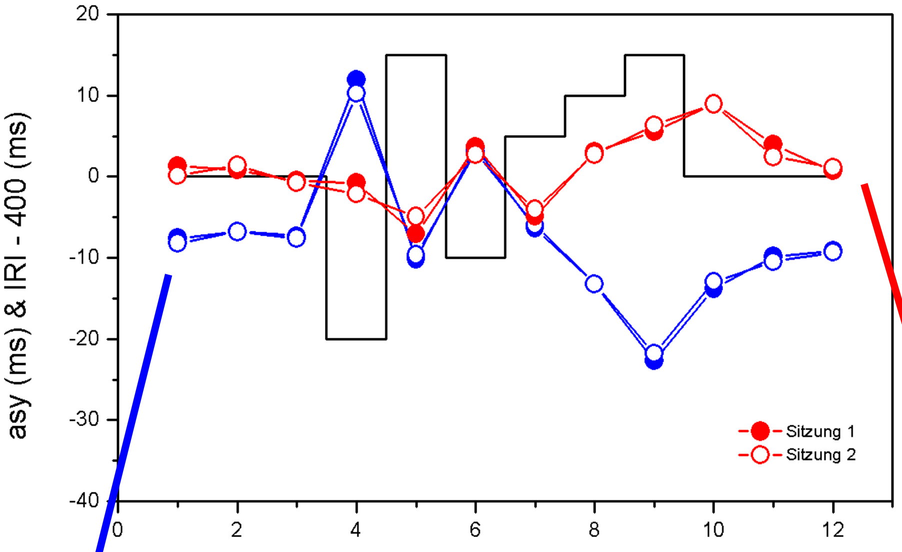


Response of the model to single perturbations: Effects on asynchronies and interresponse time



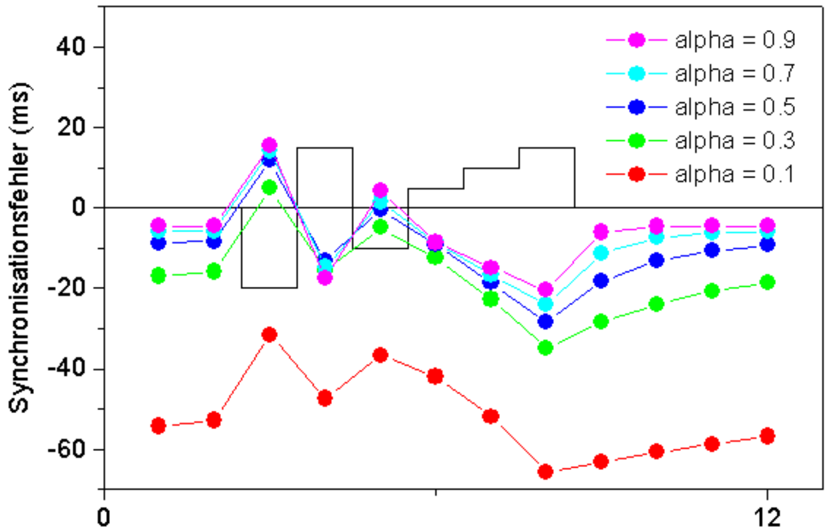
Observed and predicted response to irregular perturbation patterns (A. Fuchs, 2006)

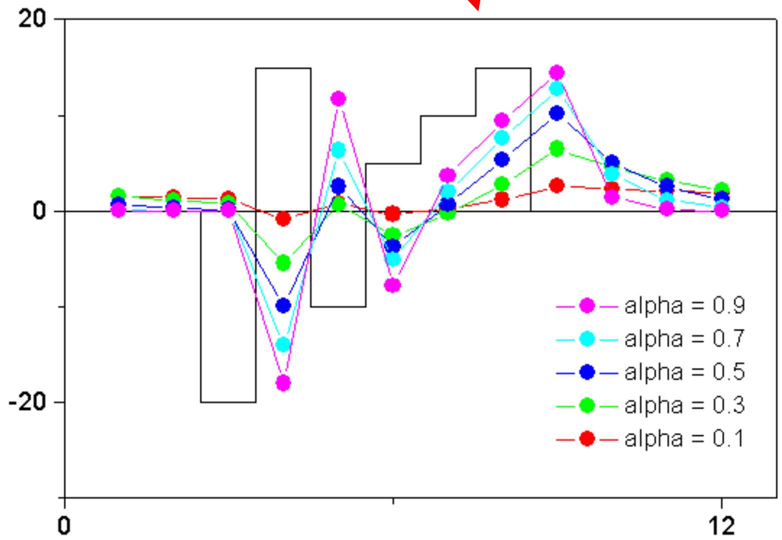
Antje Fuchs



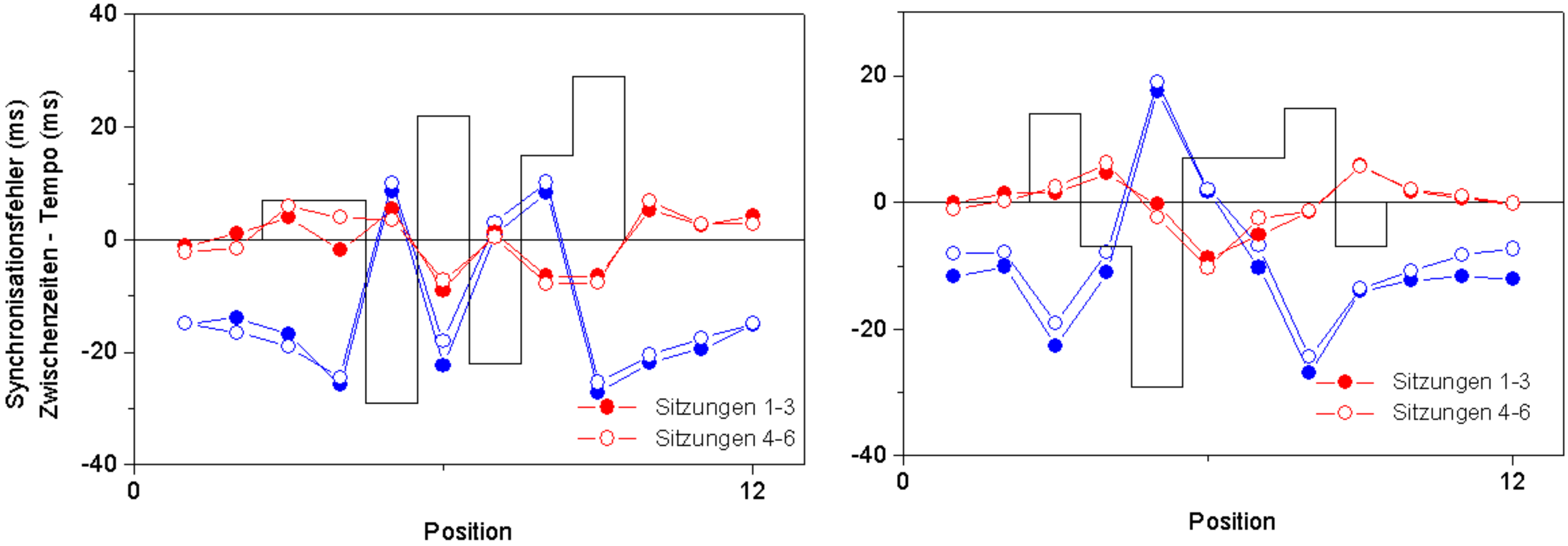
Asynchronies, A_n

Interresponse Intervals, I_n





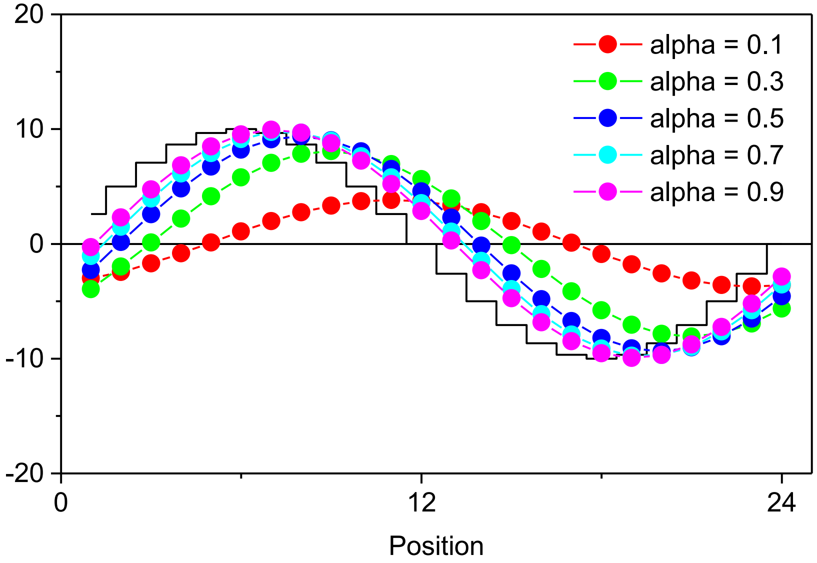
Response to repeating irregular perturbation patterns: No implicit learning (*Hebb effect*) of massively repeated patterns!

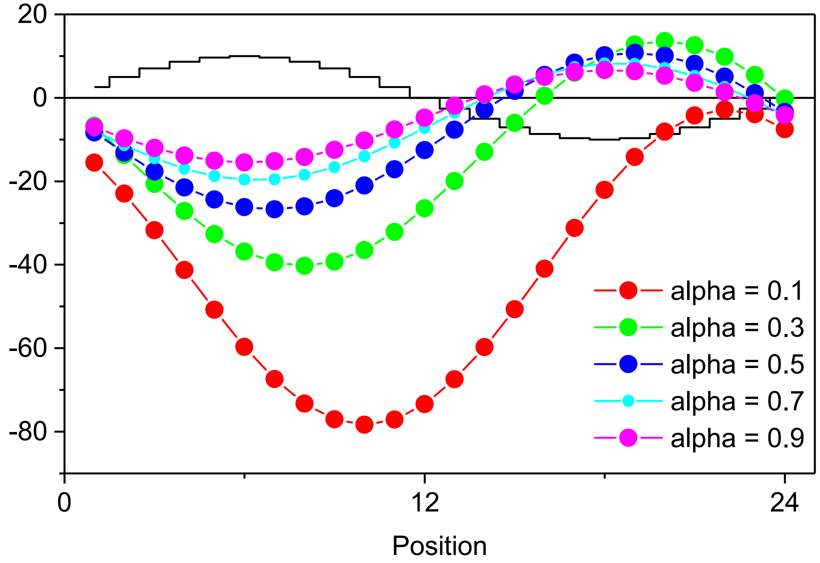


Predicted response of the model to sinusoidal tempo changes

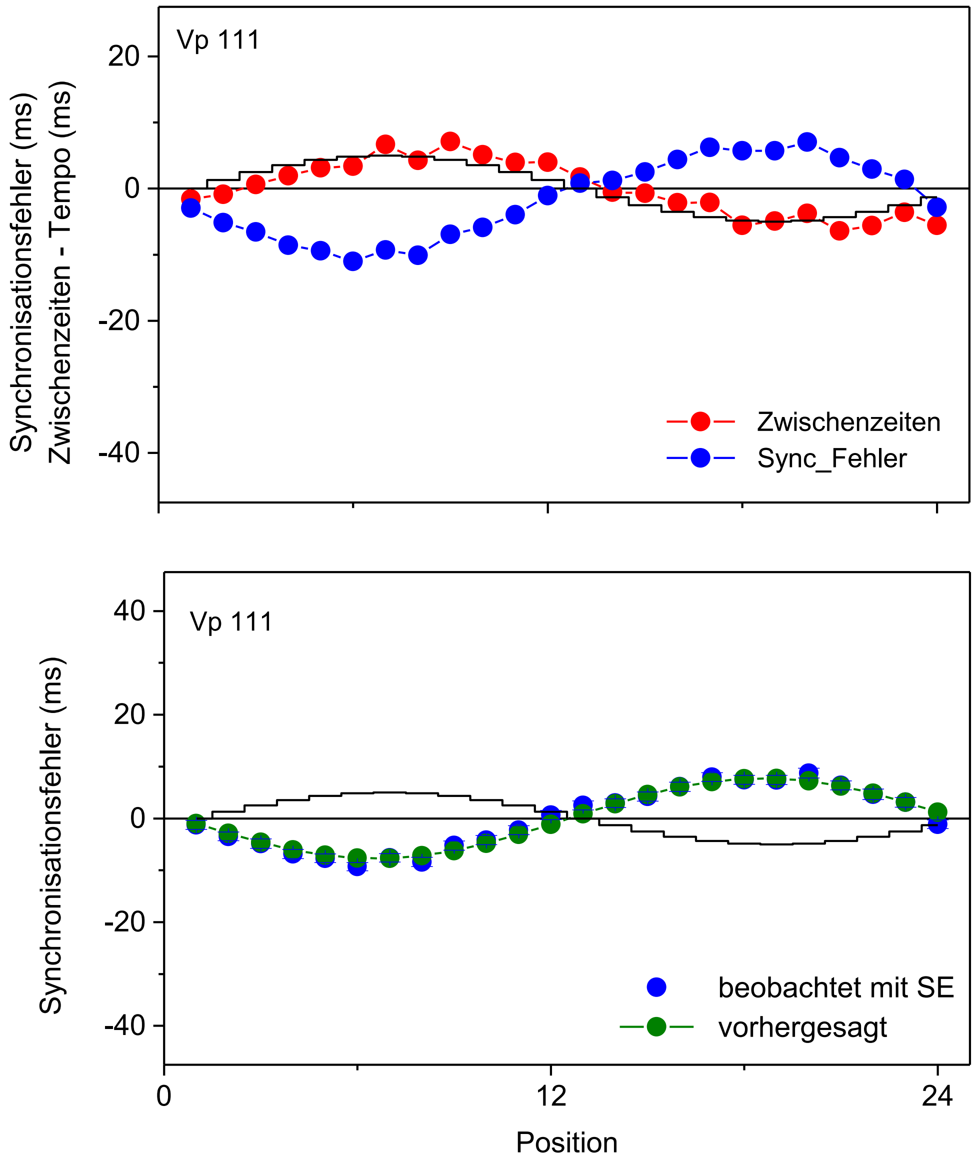
Effects on asynchronies, A

Effects on IRIs, I





Observed and predicted effects of *subliminal* sinusoidal tempo-changes



α = .625

Conclusions

In spite of its simple linear assumptions, the two-level synchronisation model has turned out extremely robust and more successful empirically than more complex competitors (e.g., oscillator models).

- Extension and successful tests of model to
  - two-person interactions

    Simplifying assumption: each person serves as metronome for partner

    Vorberg, 2005; Repp & Keller, 2009, 2010

  - string quartet performance

    Wing, Endo, Bradbury, and Vorberg (in prep.)

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With or without feedback loop?

Open-Loop

timekeeper

▼

motor
implementation

▼

Closed–Loop

timekeeper

▲

▼

motor
implementaton

sensory feedback

▲

▼

Findings problematic for the basic two-level model

Delayed auditory feedback

Wing (1977): on single tap

Freudhofen (unpublished diploma thesis, 2002): sequence of feedback delays gradually lengthened or shortend

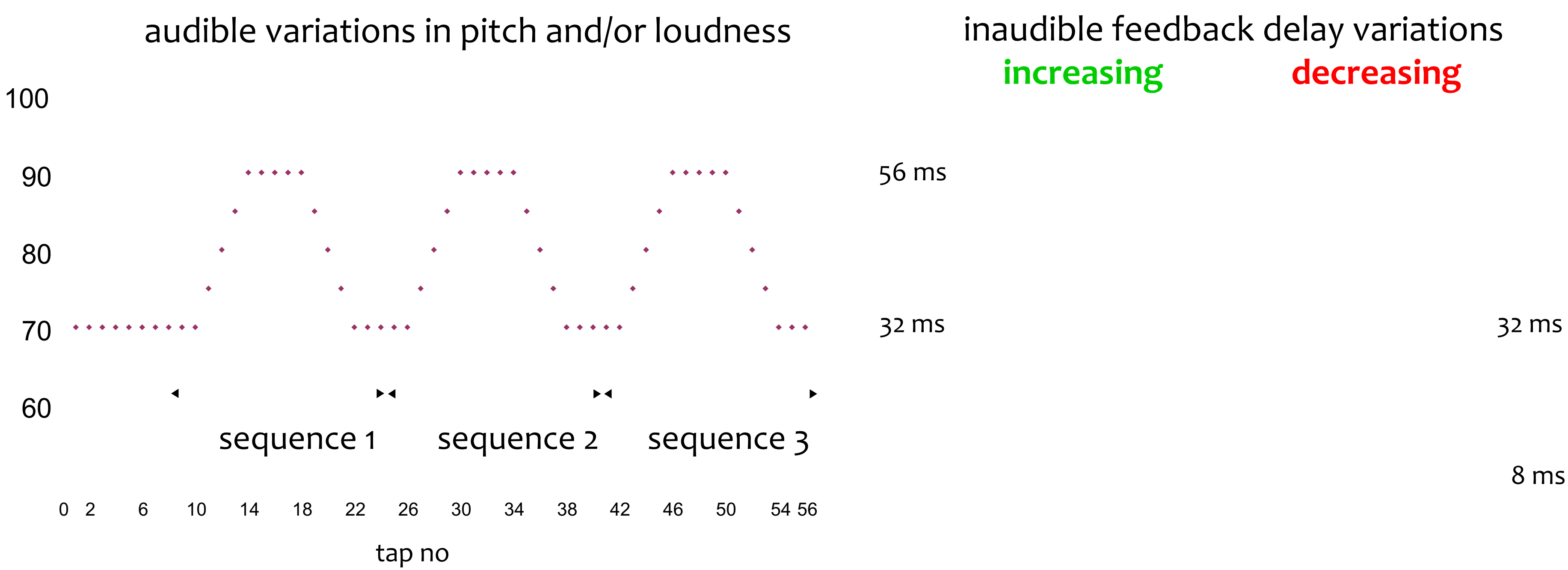
Drewing, Hennings, & Aschersleben (2002, 2003): Bimanual advantage and the amount of reafferent feedback

A. Freudhofen & D. Vorberg (2002)

effects of delaying auditory feedback in structured isochronous continuation tapping

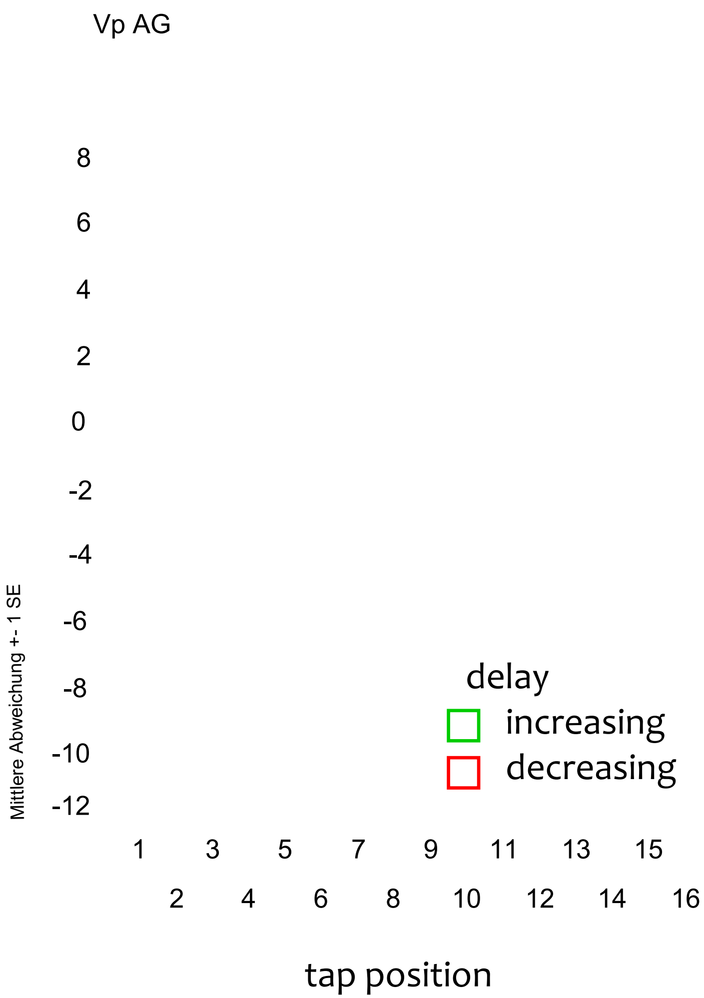
participants: 5 semi-professional musicians (jazz & pop)

Trial scheme: Pitch and loudness variations (left) varied independently of feedback delay (right)

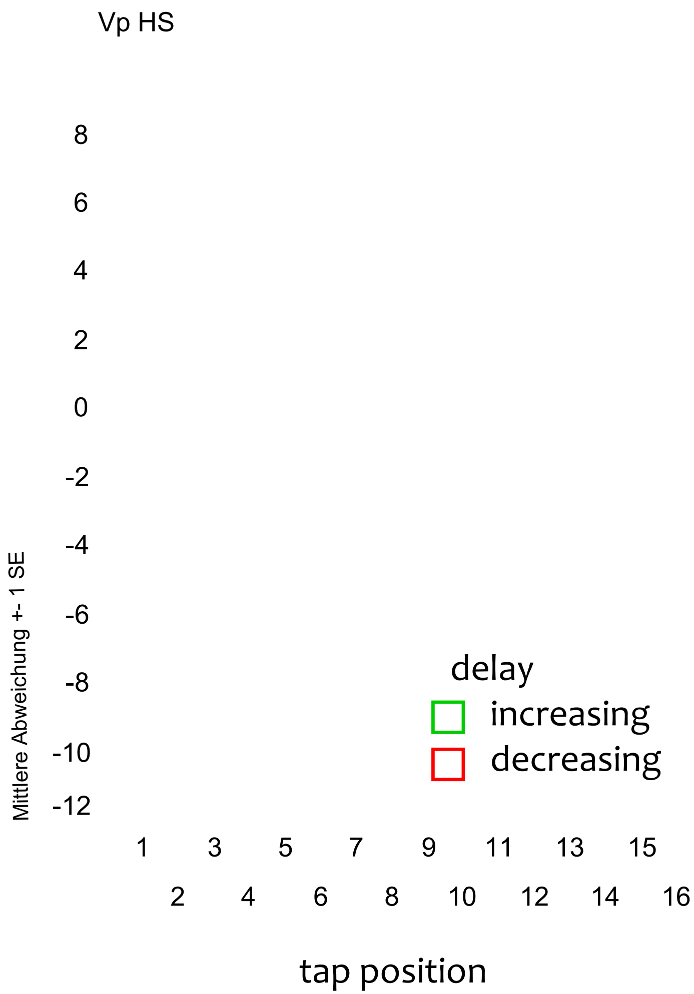


feedback delay variations
trigger both period and phase correction mechanisms in some participants

phase only

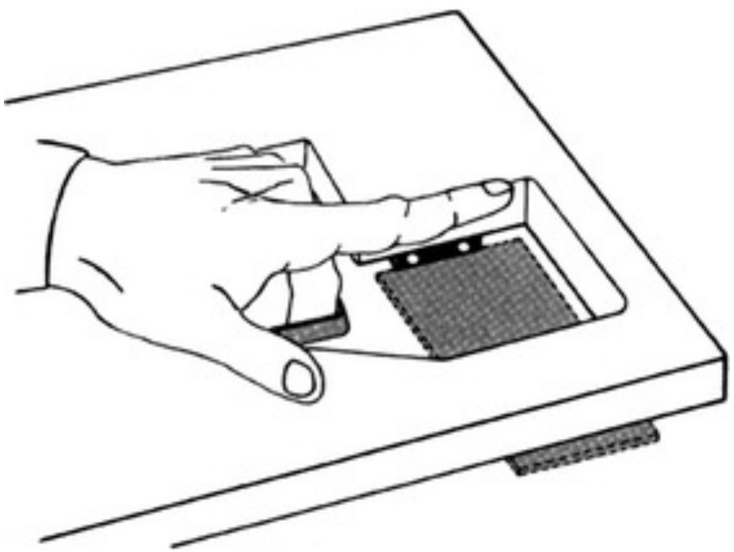


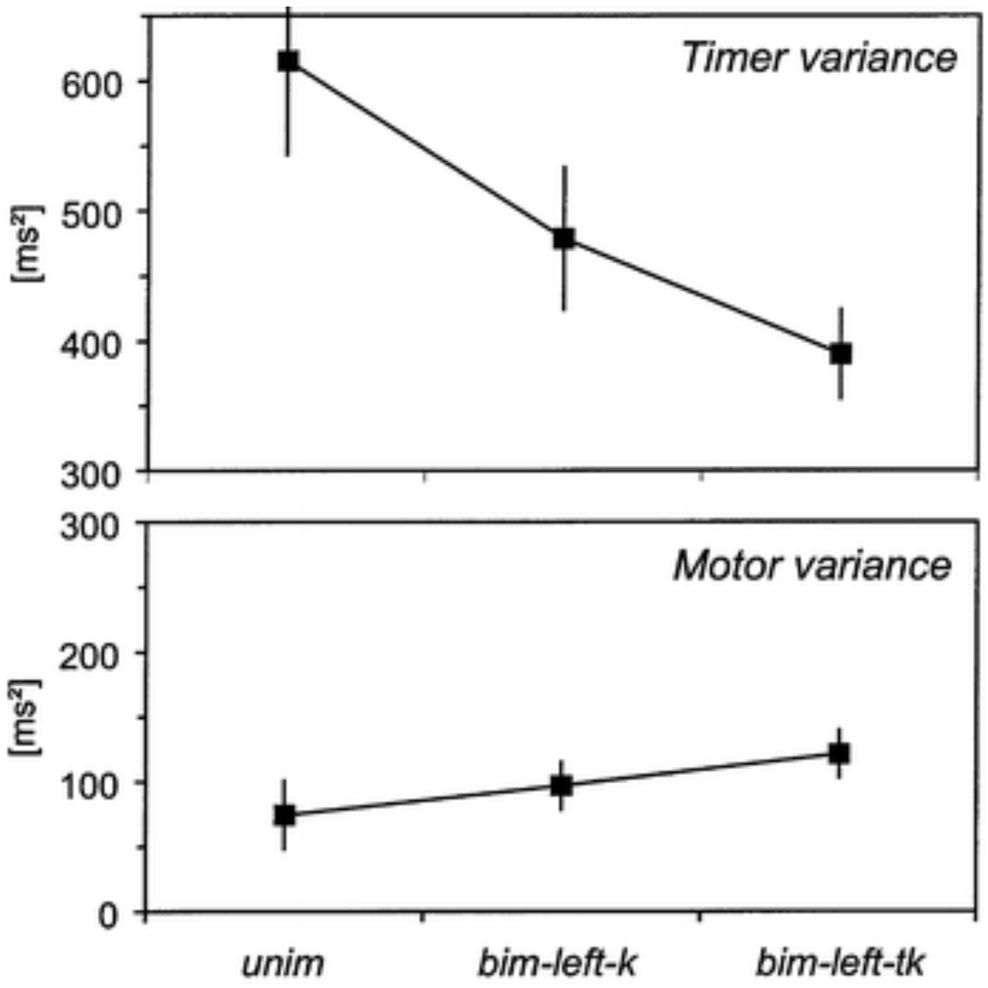
period + phase



The bimanual timing advantage depends on the *amount of reafferent feedback*

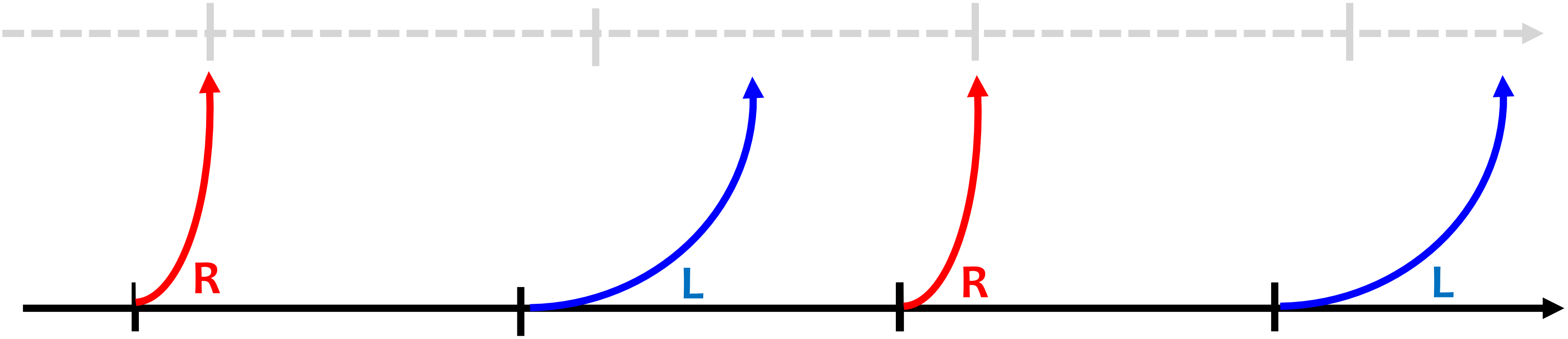
(Drewing, Hennings, & Aschersleben, QJEP, 2003)



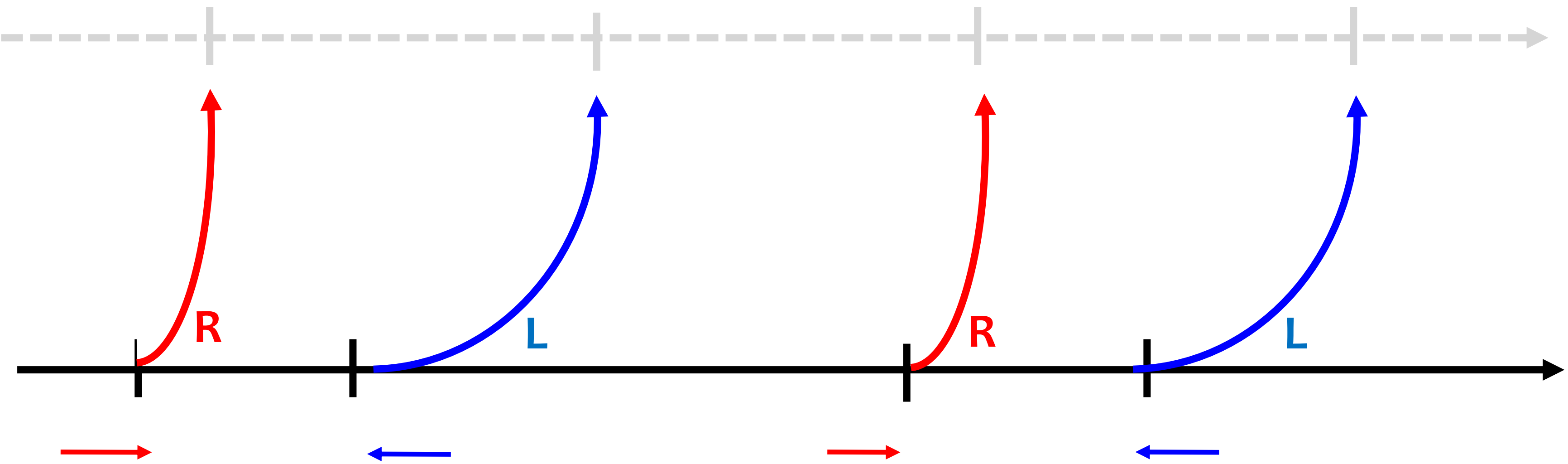


Alternating two-handed isochronous tapping with differential feedback delays (K. Drewing, Paris 2006)

perceived if produced timekeeper intervals are equal:



observed production:



Action-effect version of the two-level continuation model

Challenging question:

How to modify the model to account for feedback effects without invaliditating the *acvf* predictions of the original model?

What is timed -

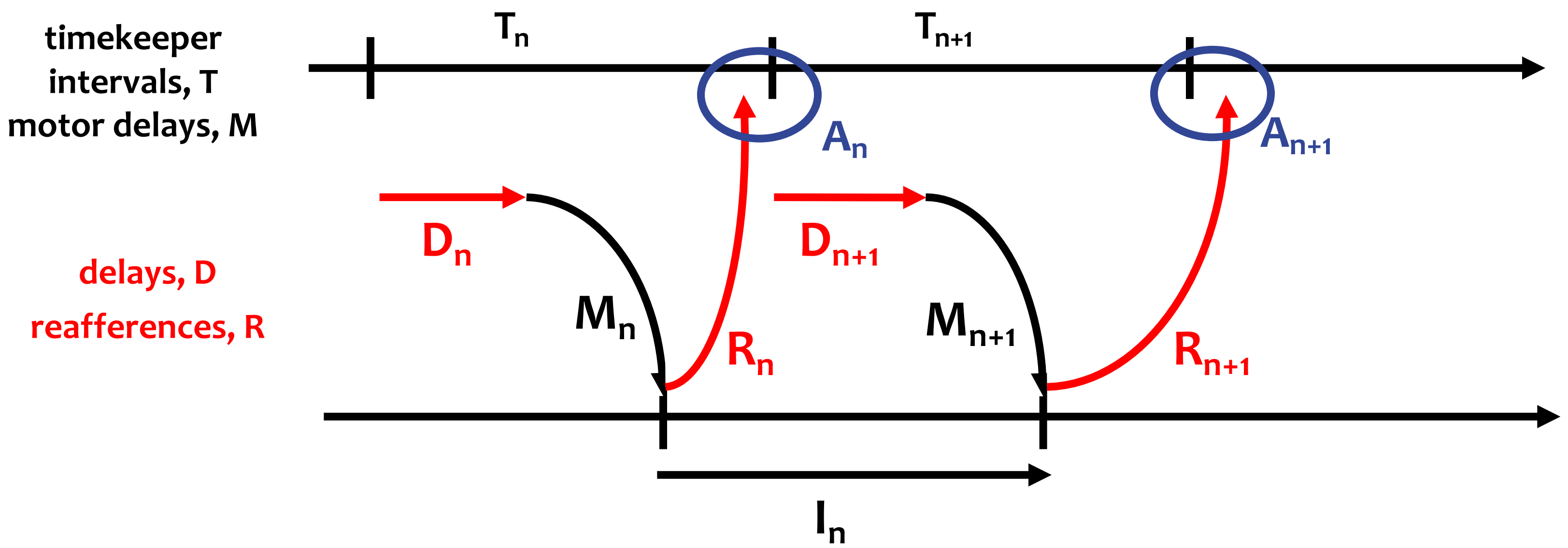
onset of movement commands?

or **expected action effects**?

Basic assumption:

The timekeeper specifies **temporal goals** for action effects, rather than **time-marks for the initiation of actions**

Action-effect timing: Assumptions
(Vorberg, RPPW, 2007)



Definitions

D1 $A_n = T_n - (D_n + M_n + R_n)$

D2 $D_n = D'_n + d_n$

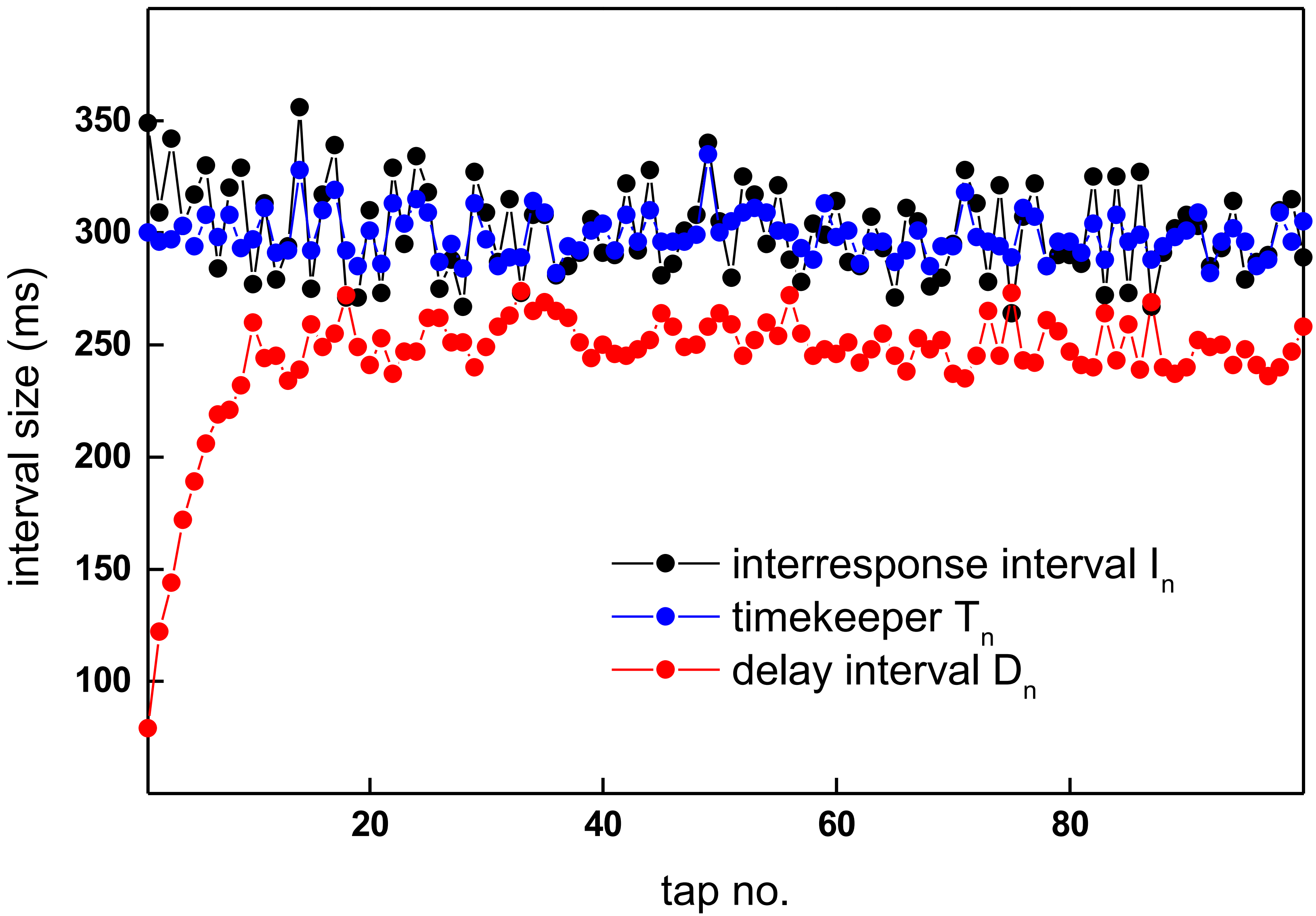
Assumptions

A1 $\{T'_n\}, \{D'_n\}, \{M_n\}, \{R_n\}$ i.i.d. random variables

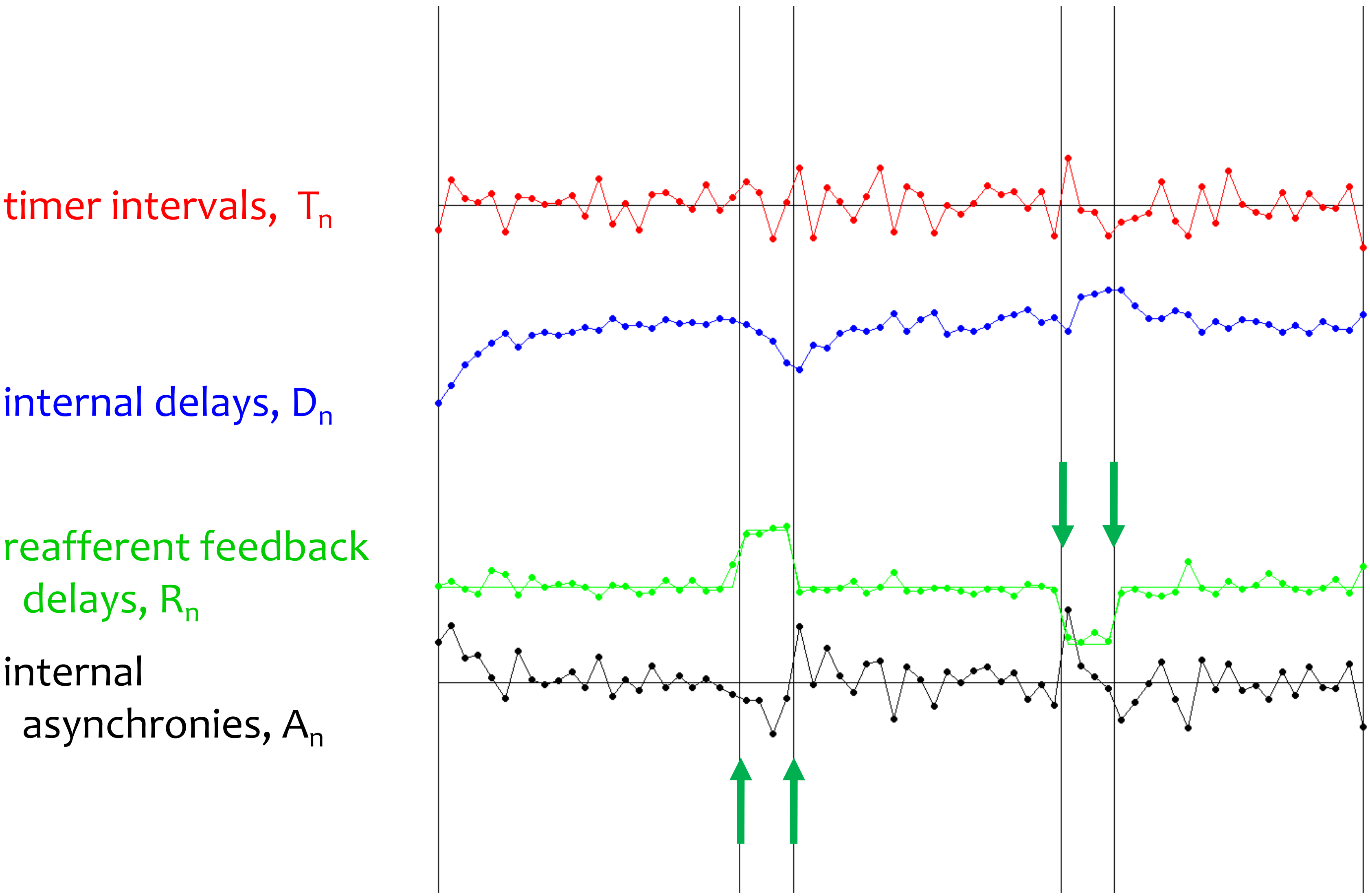
A2 period correction: $d_{n+1} = d_n - \alpha A_n$

A3 phase correction: $T_{n+1} = T'_{n+1} + \beta A_n$

Monte Carlo data (α=.25, β=.0)



The Reafference Model in action: Adjusting to global tempo while responding to local feedback-perturbations



Finale:
The Crucial Question

The reafference model correctly predicts and describes

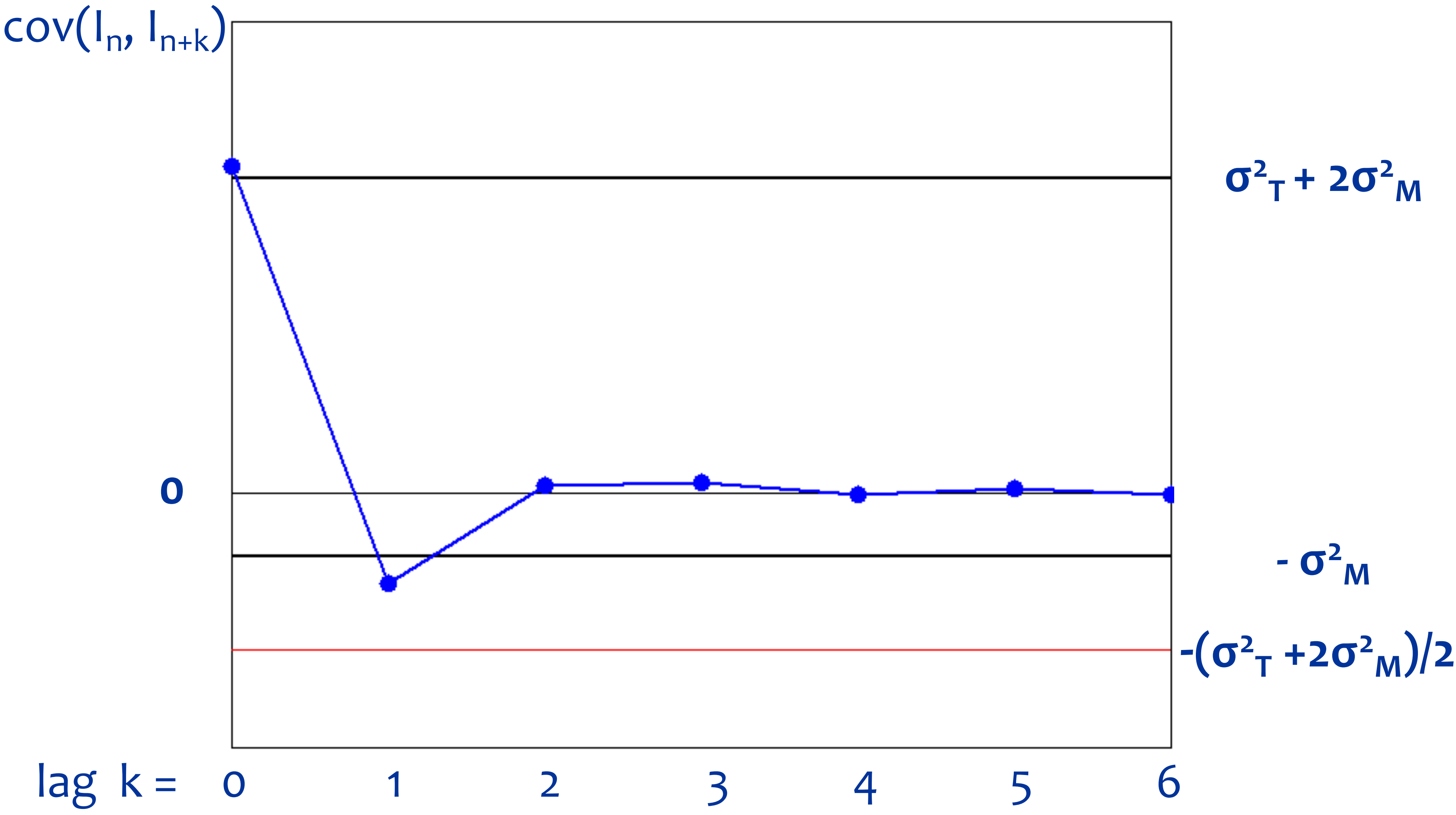
- the effects of feedback manipulations,

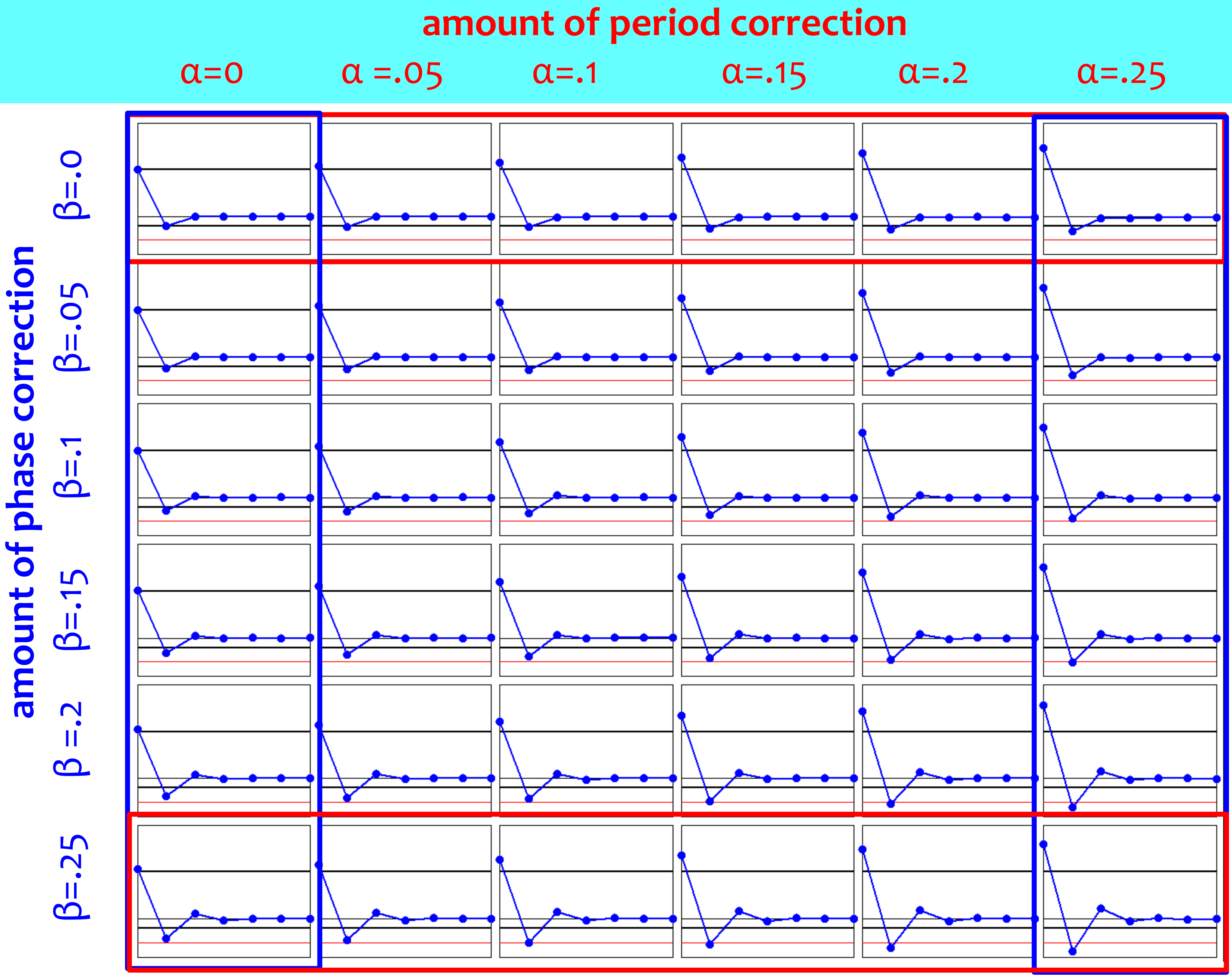
but – does it asymptotically (‚at steady state‘) predict

- the *acvf* shape diagnostic of the Two-Level model?

Asymptotic IRI acvf, generated by model extended by linear period and/or phase correction

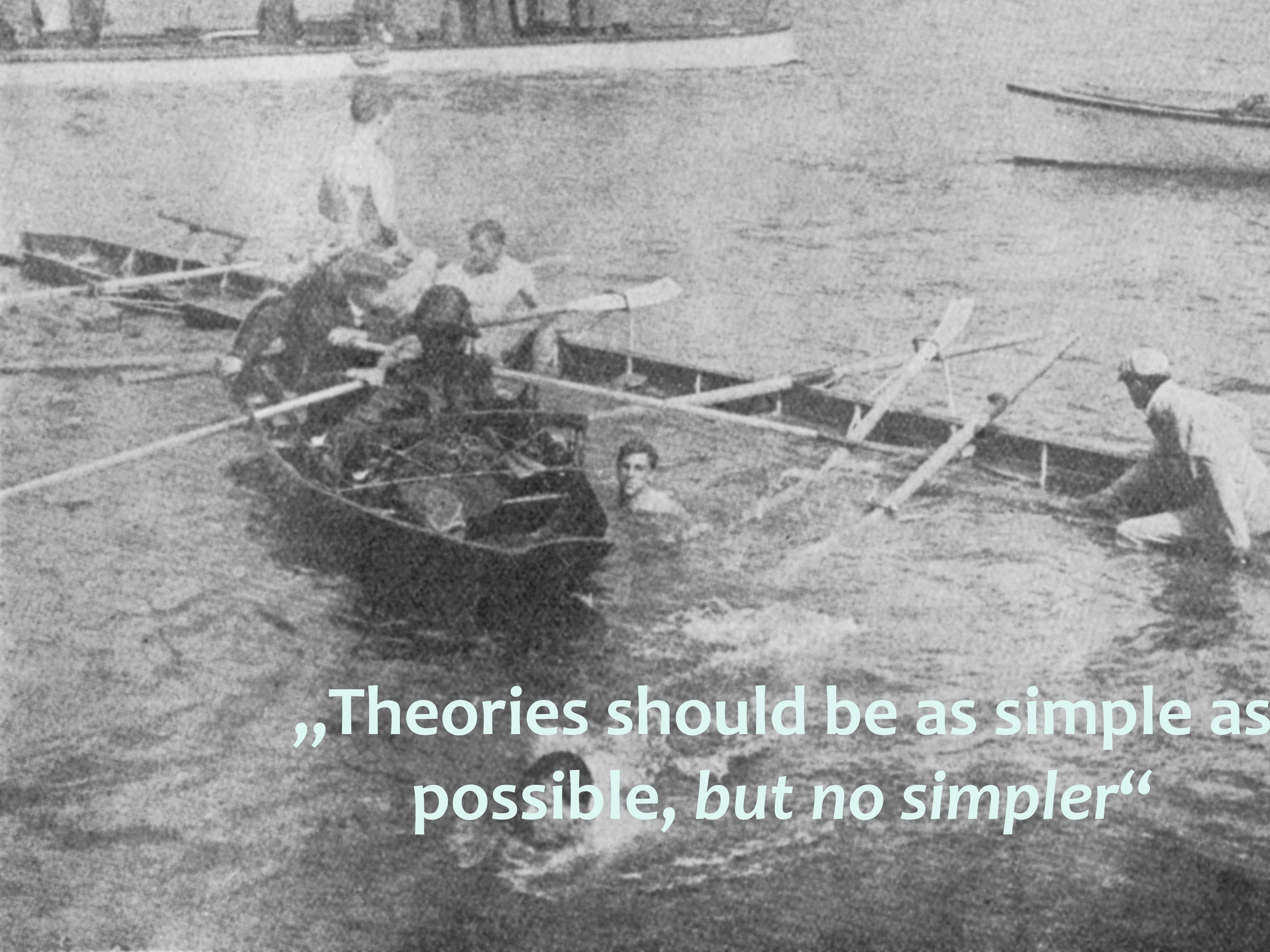
(display scheme, illustrated on simulated WK model, i.e., with $\alpha = \beta = 0$)




amount of period correction
α=0
α =.05
α=.1
α=.15
α=.2
α=.25
amount of phase correction
β=.0
β=.05
β=.1
β=.15
β =.2
β=.25

Conclusions

- Wing‘s *open-loop* two-level model closely approximates more realistic and flexible *closed loop* models based on reafferent signals, i.e., the *discrepancies between predicted and actual action effects.*
- The model‘s distinction between *periphal* and *central sources* of temporal noise remains the cornerstone for cognitive and neuroscientific analyses of the control of timing precision and its disturbances.
- This serves to show the eminent *heuristic value of linear models*.
- Quote Albert Einstein:


„Theories should be as simple as possible, *but no simpler*“


Thanks
for your attention!

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5 Hans-Henning Schulze (Marburg)
1 Andras Semjen (Marseille)
2 Alan Wing (Birmingham)

Recommended readings

Wing, A. M. (2002). Voluntary timing and brain function: An information processing approach. *Brain and Cognition*, **48**, *7-30.*

Wing, A. M., & Beek, P.J. (2002). Movement timing – a tutorial. In: Prinz, W. & Hommel, B. (Eds.). *Attention* & *Performance* 19. Oxford University Press, pp 202-226.

Buonomano, D.V., & Kamarkar, U.R. (2002). How do we tell time? *Neuroscientist*, **8**, 42-51.

Ivry, R.B., & Spencer, R.M.C. (2004). The neural representation of time. *Current Opinion in Neurobiology*, **14**, 225–232.

Grondin, S. (2010). Timing and time perception: A review of recent behavioral and neuroscience findings and theoretical directions. *Attention, Perecption & Psychophysics*, **72**, 561-582.