# Optimal time interval reproduction in a neural circuit model

**Katharina M Bracher[1,2] and Kay Thurley[1,3]**
k.bracher@campus.lmu.de

1 Faculty of Biology, Ludwig-Maximilians-Universität München, Germany
2 Graduate School of Systemic Neurosciences, Ludwig-Maximilians-Universität München Munich, Germany
3 Bernstein Center for Computational Neuroscience Munich, Germany

Graduate School of Systemic Neurosciences
LMU Munich

bccn munich

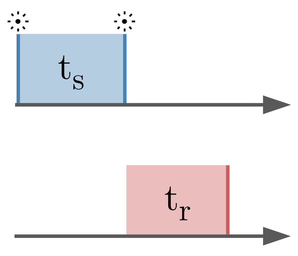
## Introduction

Sensory information is combined with expectations (based on prior knowledge) to drive behaviors.
The interaction of current sensory input and expectations is likely subject to error minimization.

### Psychophysical characteristics of magnitude estimation

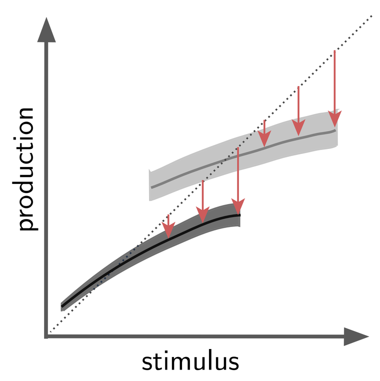
Magnitude estimation shows characteristic effecs:

- Regression effect
- Scalar variability
- Range effect
- Sequential effect




$t_s$ : stimulus interval
$t_r$ : reproduced interval

Time reproduction is one of the behavioral methods to investigate error minimization and related optimal behavioral strategies.



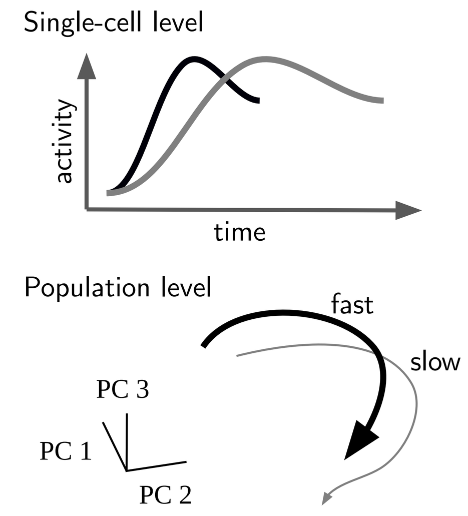

### Timing by temporal scaling

Recordings in the medial frontal cortex (MFC) show:

- Firing rate profiles are temporally scaled to match the produced intervals
- Population activity evolves along an invariant neural trajectory at different speeds
- Controling timing of future movements by adjusting an internal speed command
- Speed command is updated after stimulus presentation based on the error between prediction (derived from a simulated motor plan) and the actual stimulus duration.

### Circuit model

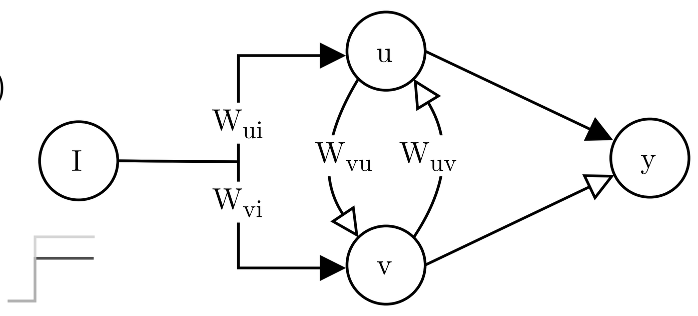
- Coordinates movement times using ramping activity towards a threshold.
- Update of speed comand based on error signal to minimize timing errors.




## Model Description

### Basic circuit

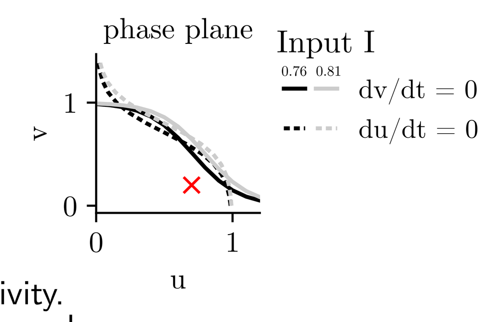
$$\tau\frac{du}{dt} = -u + \theta(W_{uI}I - W_{uv}v + \eta_u)$$
$$\tau\frac{dv}{dt} = -v + \theta(W_{vI}I - W_{vu}v + \eta_v)$$
$$\tau\frac{dy}{dt} = -y + W_{yu}u - W_{yv}v + \eta_y$$




Flexibel speed control can be achieved by a simple model consisting of three units u, v, y that represent population activity.

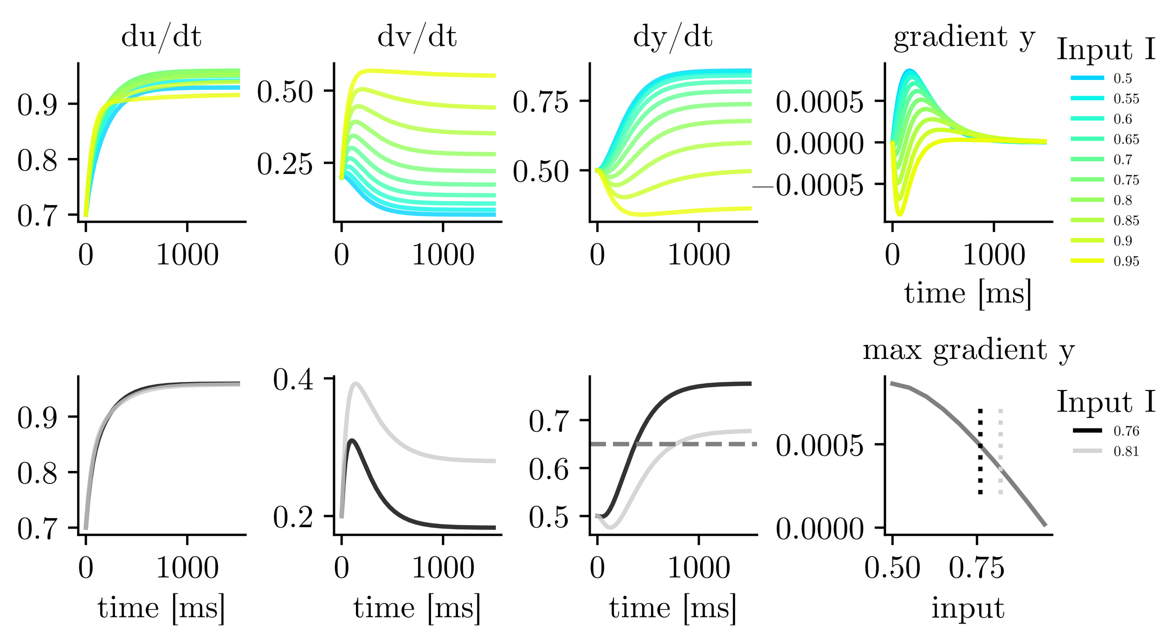
Stochastic synaptic inputs are modeled as independent white noise $\eta$ with standard deviation $\sigma$.

- Two mutually inhibitory units u, v receive shared tonic input I.
- Inputs to u, v are governed by a sigmoidal activation function $\theta$.
- The readout unit y receives excitatory and inhibitory inputs from u and v.
- This results in ramp-like activity in y.




### Input regime

- The input to the circuit controls at which speed the readout unit increases its activity.
- Increasing the input I to u and v corresponds to moving their nullclines in the phase plane.




Inverse relation of slope and input:

- Higher inputs I correspond to smaller gradients in y.
- Lower inputs I correspond to larger gradients in y.

Connecting the slope of y and a fixed threshold $y_{th}$:

- For higher I, the threshold is reached after a longer time interval.
- For lower I, the threshold is reached after a shorter time interval.

The activity in y is scaled such that the threshold is reached at different times.
I determines the time interval after which y reaches the fixed threshold $y_{th}$.

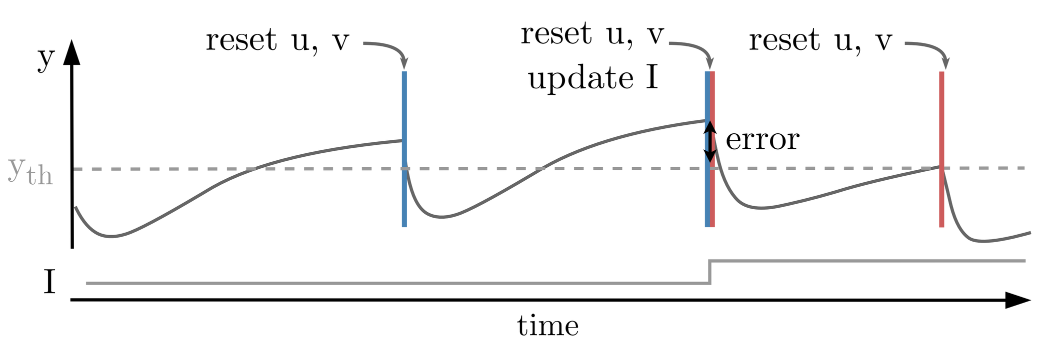
### Update and reset mechanism

In interval reproduction experiments, a stimulus interval is presented and has to be reproduced.
Reaching a threshold $y_{th}$ can be understood as movement initiation time.

Update mechanism that flexibly adjusts I:

- Adjusting I based on an error signal controlls the reporduced time interval.
- The error signal is based on the difference between the level y reached after the stimulus presentation and the threshold $y_{th}$.
- The error is weighted by an update parameter K.

$$\tau\frac{dI}{dt} = sK(y - y_{th})$$



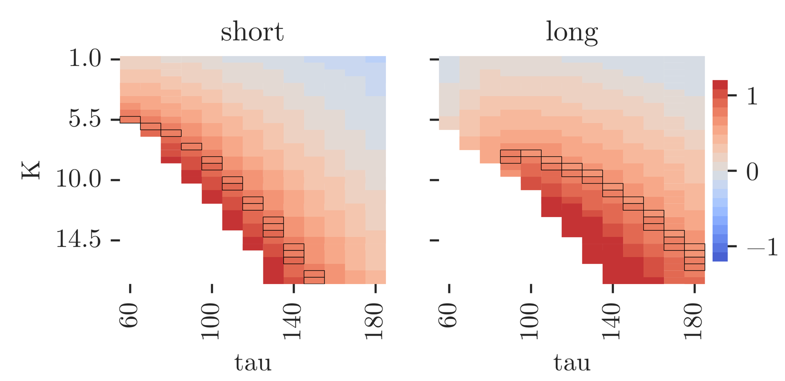

Reset mechanism:

- After stimulus presentation u and v receive a transient input $I_r$ to reset the dynamics for the time reproduction.

$$\tau\frac{du}{dt} = -u + \theta(W_{uI}I - W_{uv}v + \eta_u - I_r)$$
$$\tau\frac{dv}{dt} = -v + \theta(W_{vI}I - W_{vu}v + \eta_v + I_r)$$

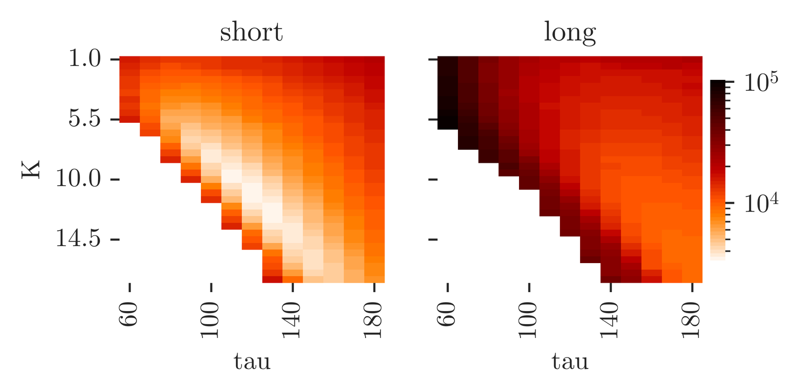
## Parameter Tuning

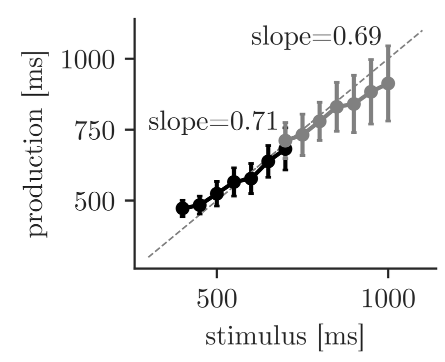
### Behavioral plausible slopes

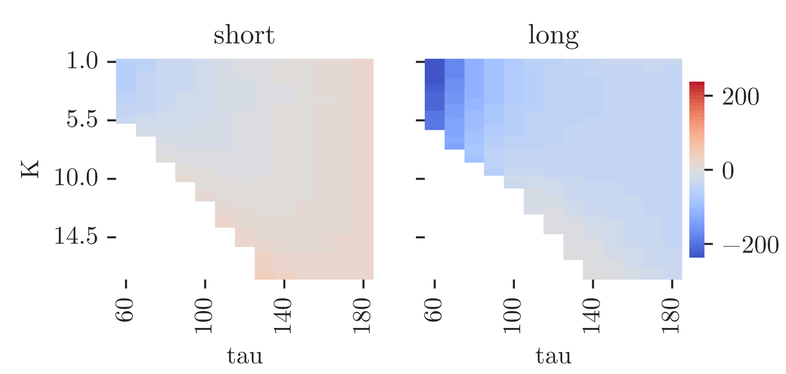



### Optimal update parameter

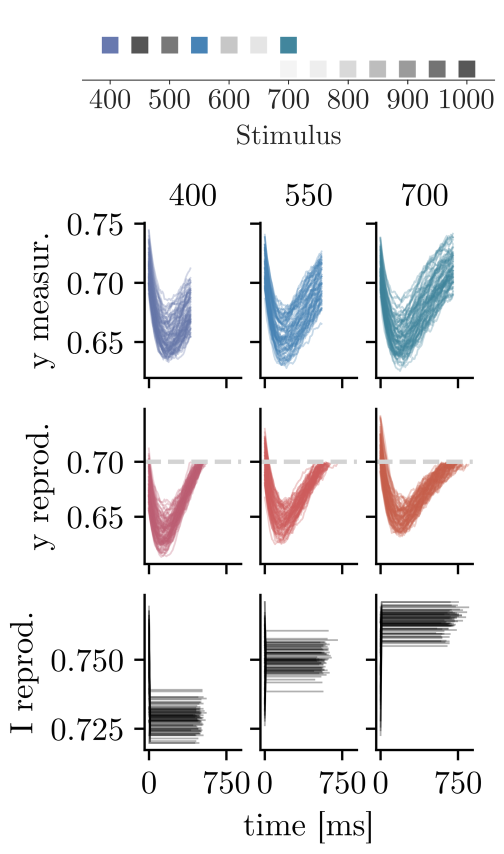
$$\mathrm{MSE} = \mathrm{BIAS}^2 + \mathrm{VAR}$$
$$\mathrm{BIAS}^2 = \frac{1}{S}\sum_{i=1}^{S}(\bar{t_{r_i}} - t_{s_i})^2$$
$$\mathrm{VAR} = \frac{1}{S}\sum_{i=1}^{S}(\sigma_i^2)$$

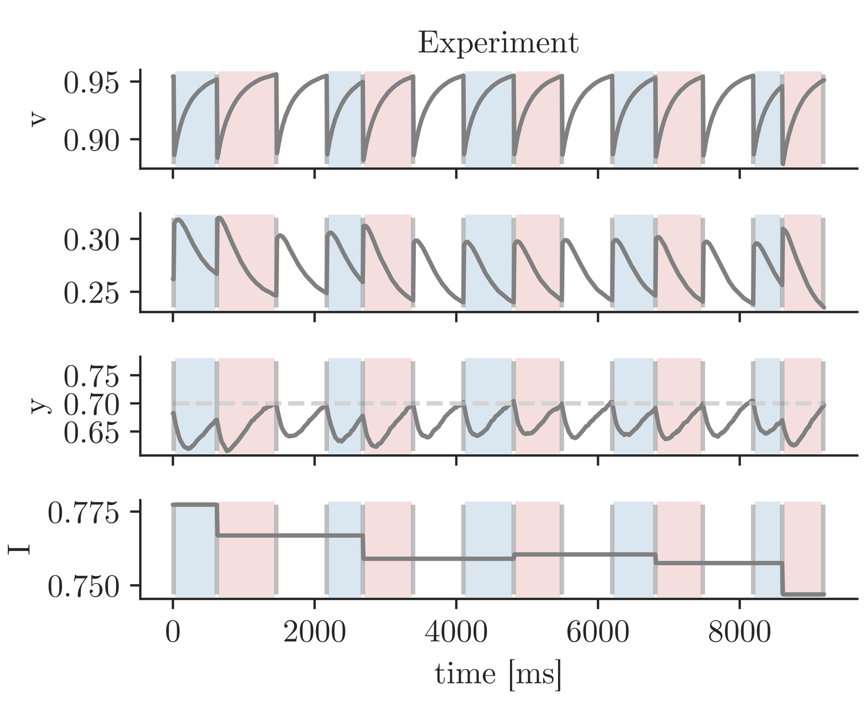



## Simulation




## Conclusion

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