Bayesian Analysis of Sensorimotor Synchronization Data

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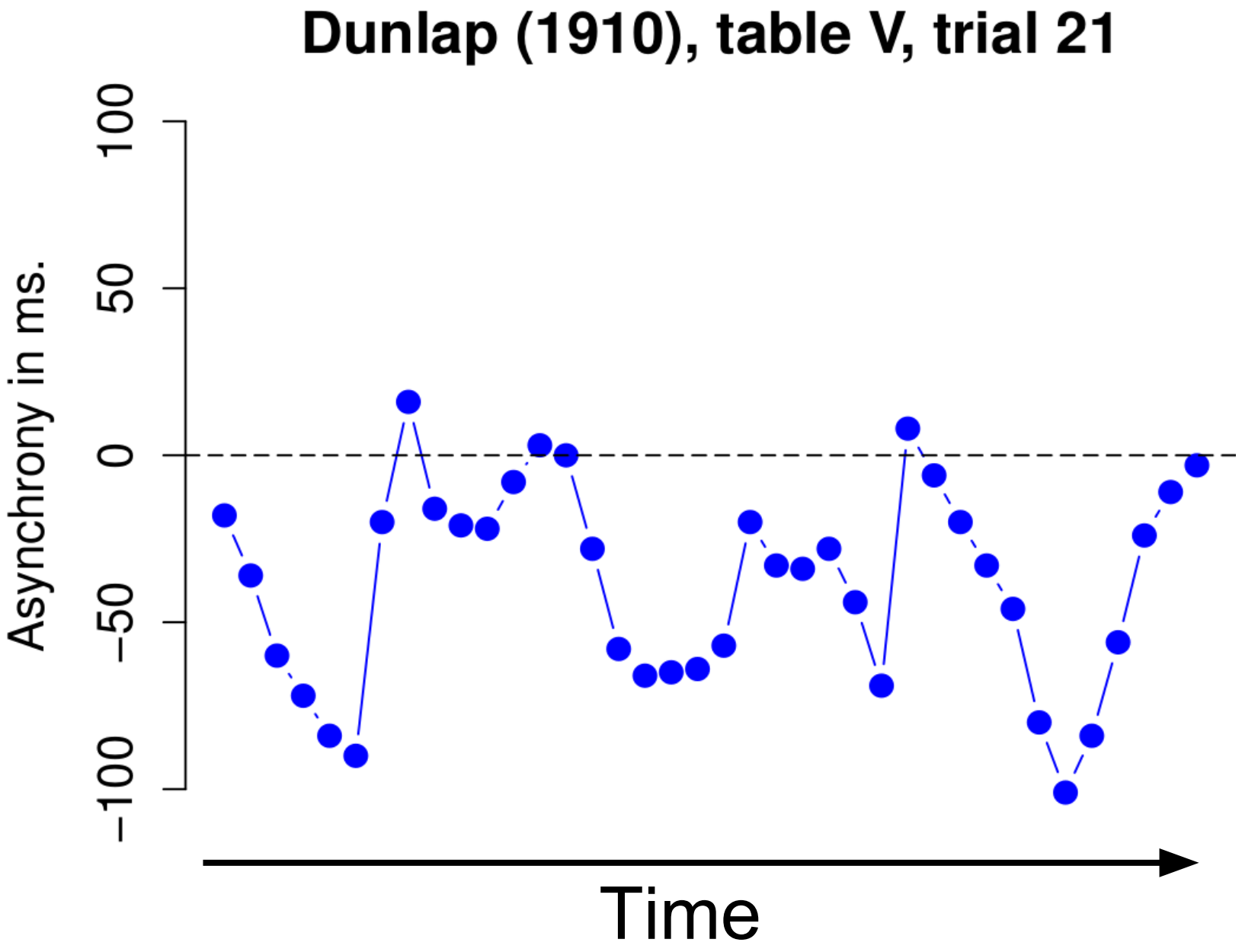
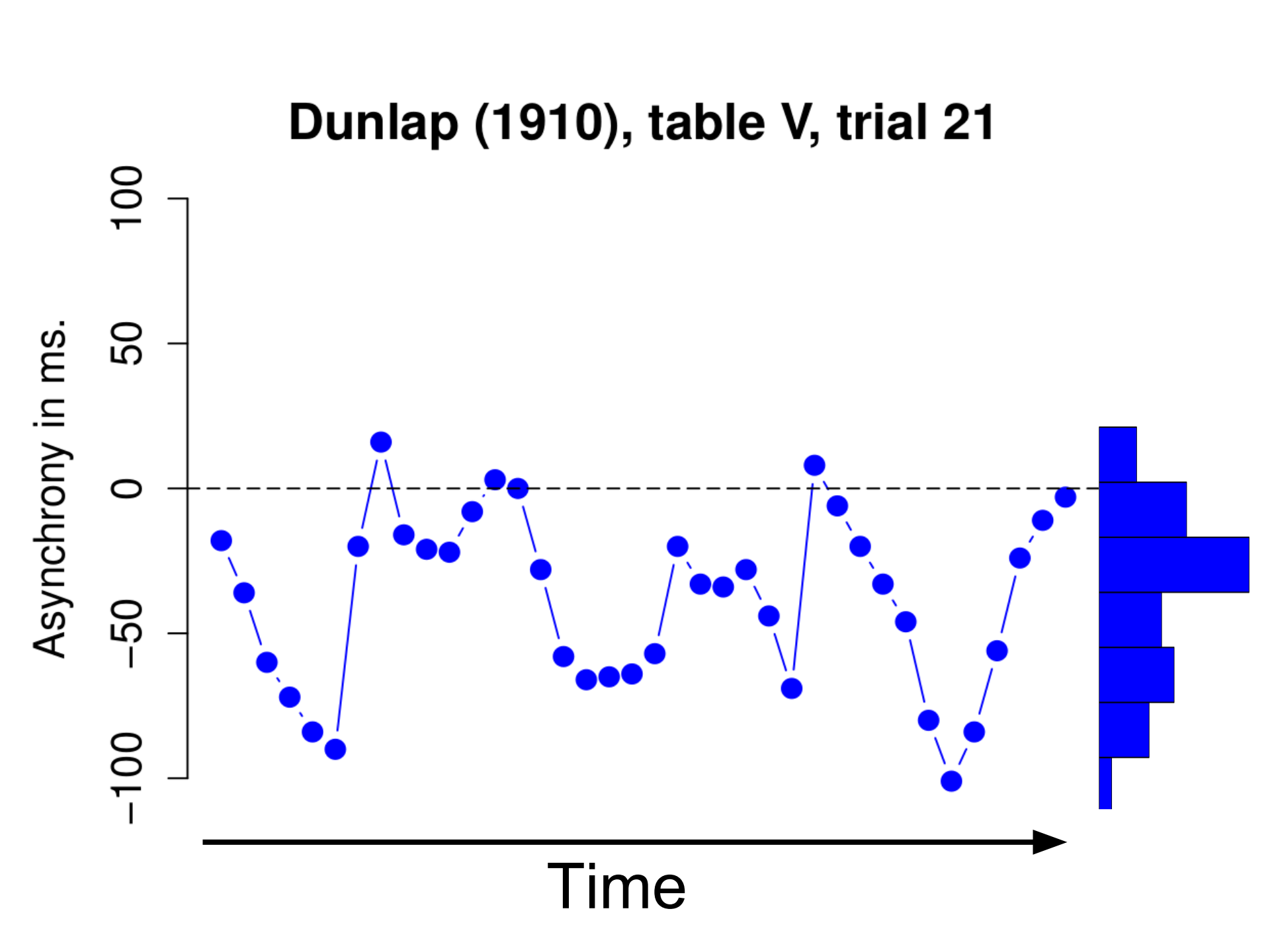
REACTIONS TO RHYTHMIC STIMULI, WITH ATTEMPT TO SYNCHRONIZE.[1]

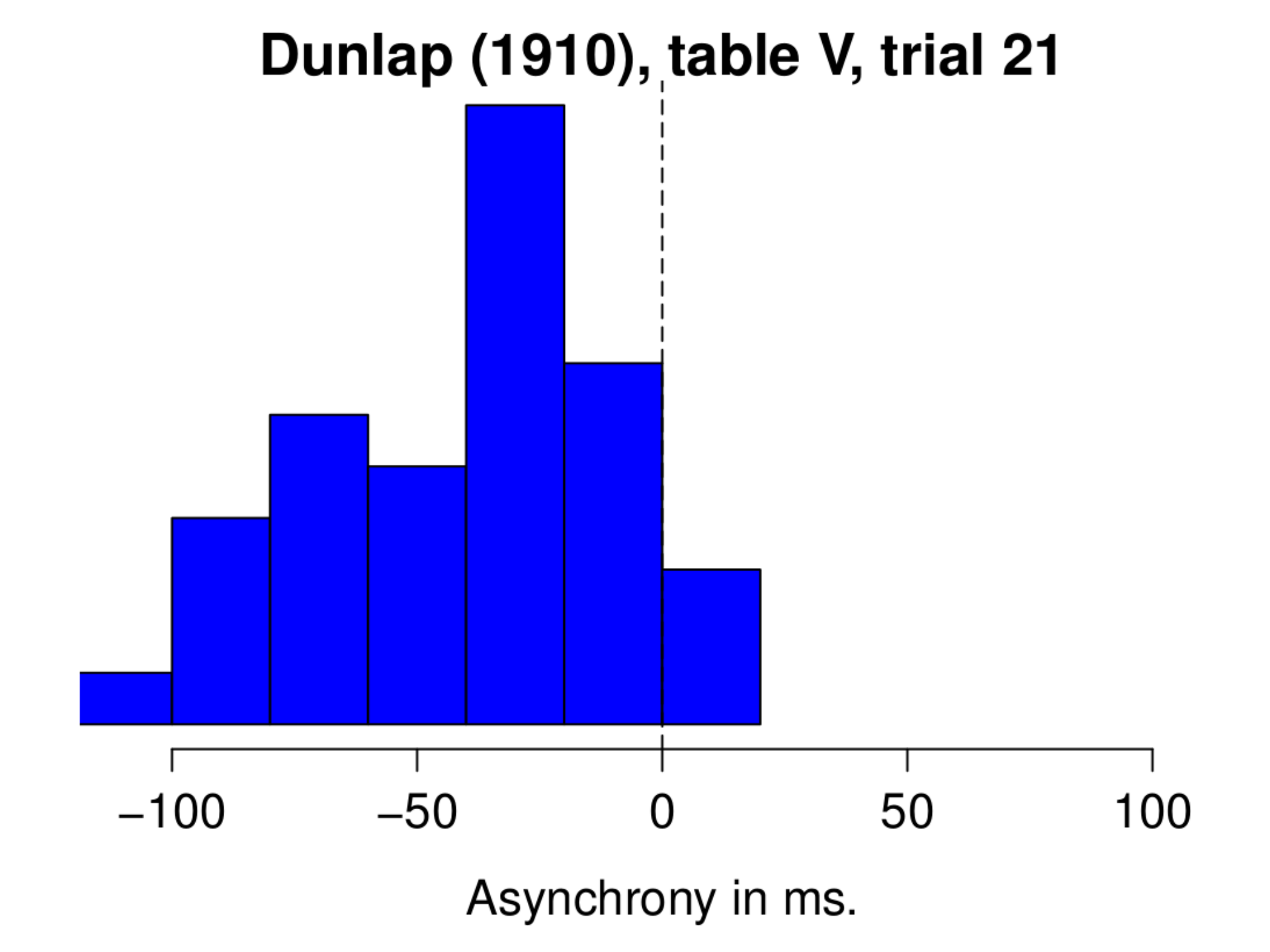
BY KNIGHT DUNLAP.

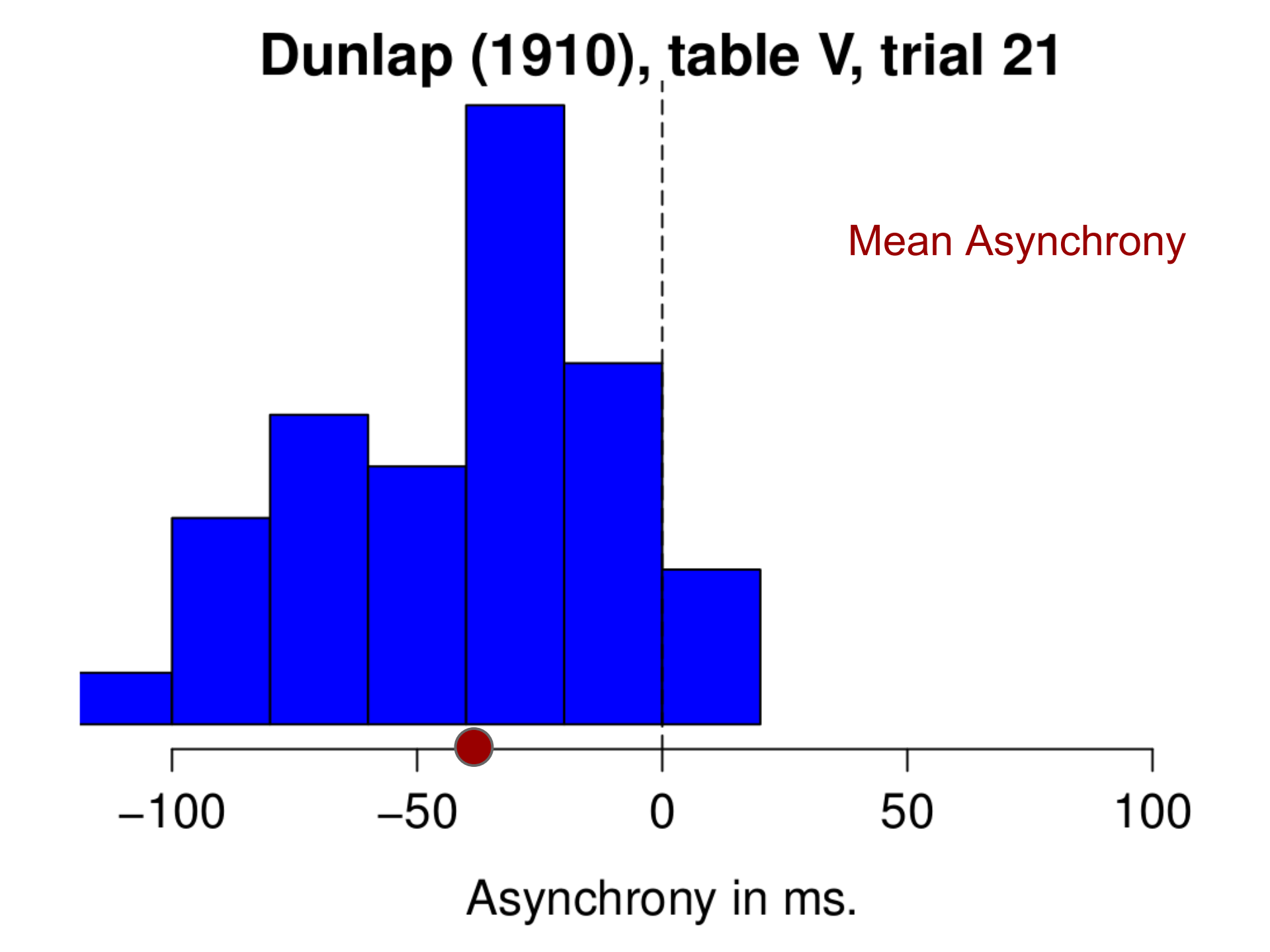
1910

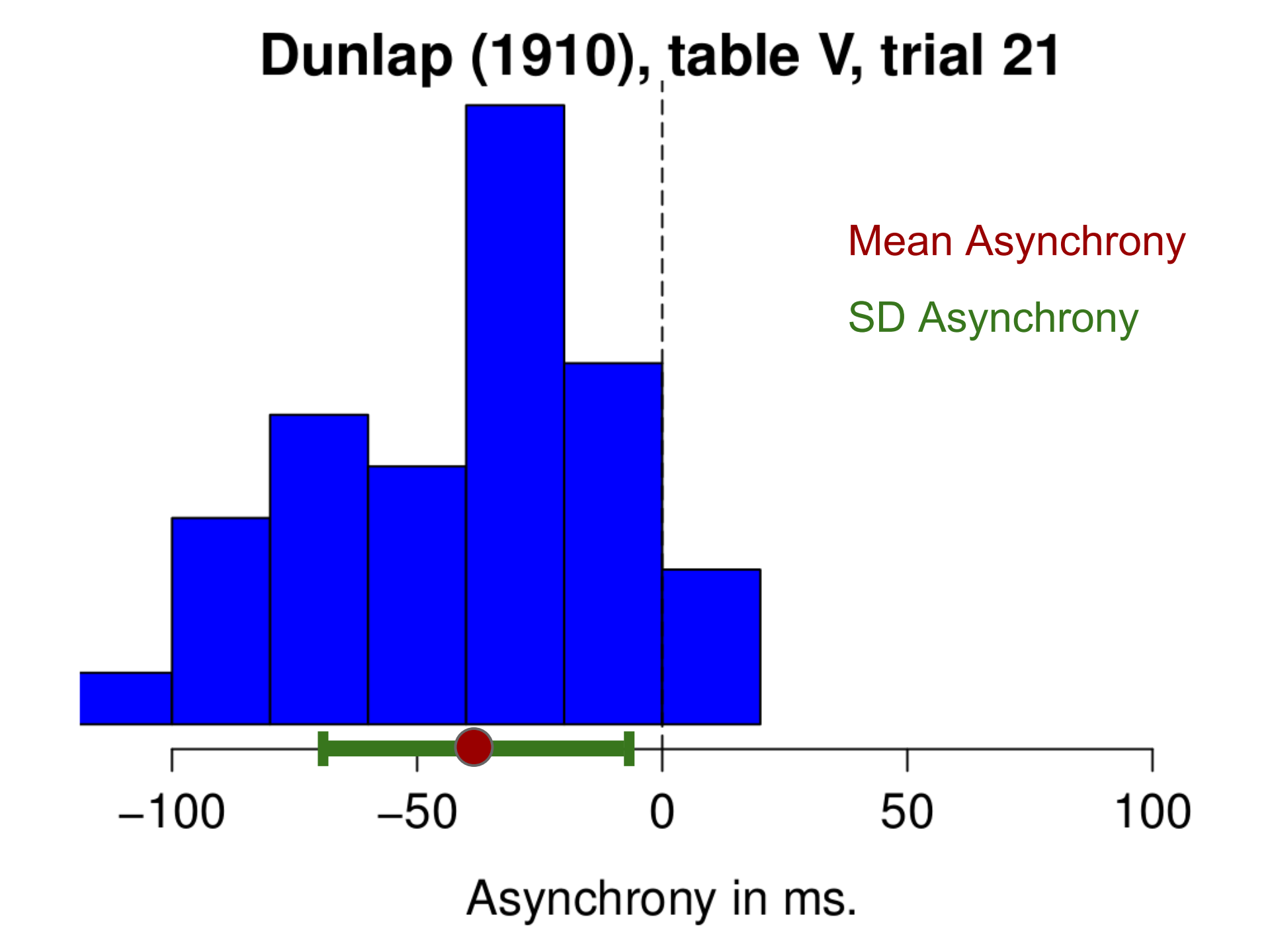
(First portion of 21, Table V.) − 18, − 36, − 60, − 72, − 84, − 52, − 38, − 20, + 16, − 16, − 21, − 22, − 8, + 3, 0, − 28, − 58, − 66, − 65, − 64, − 57, − 20, − 33, − 34, − 28, − 44, − 53, − 16, + 8, − 6, − 20, − 33, − 46, − 80, − 101, − 84, − 56, − 24, − 11, − 3.


Dunlap (1910), table V, trial 21
Asynchrony in ms.
100
50
0
−50
−100
Time


Dunlap (1910), table V, trial 21
Asynchrony in ms.
100
50
0
−50
−100
Time


Dunlap (1910), table V, trial 21
−100
−50
0
50
100
Asynchrony in ms.


Dunlap (1910), table V, trial 21
Mean Asynchrony
–100
–50
0
50
100
Asynchrony in ms.


Dunlap (1910), table V, trial 21
Mean Asynchrony
SD Asynchrony
−100
−50
0
50
100
Asynchrony in ms.

Outline

- Asynchronies tend to be normally distributed, **except for when the tapping tempo is slow.**

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- A simple model of why the distribution of asynchronies differ depending on the tempo.

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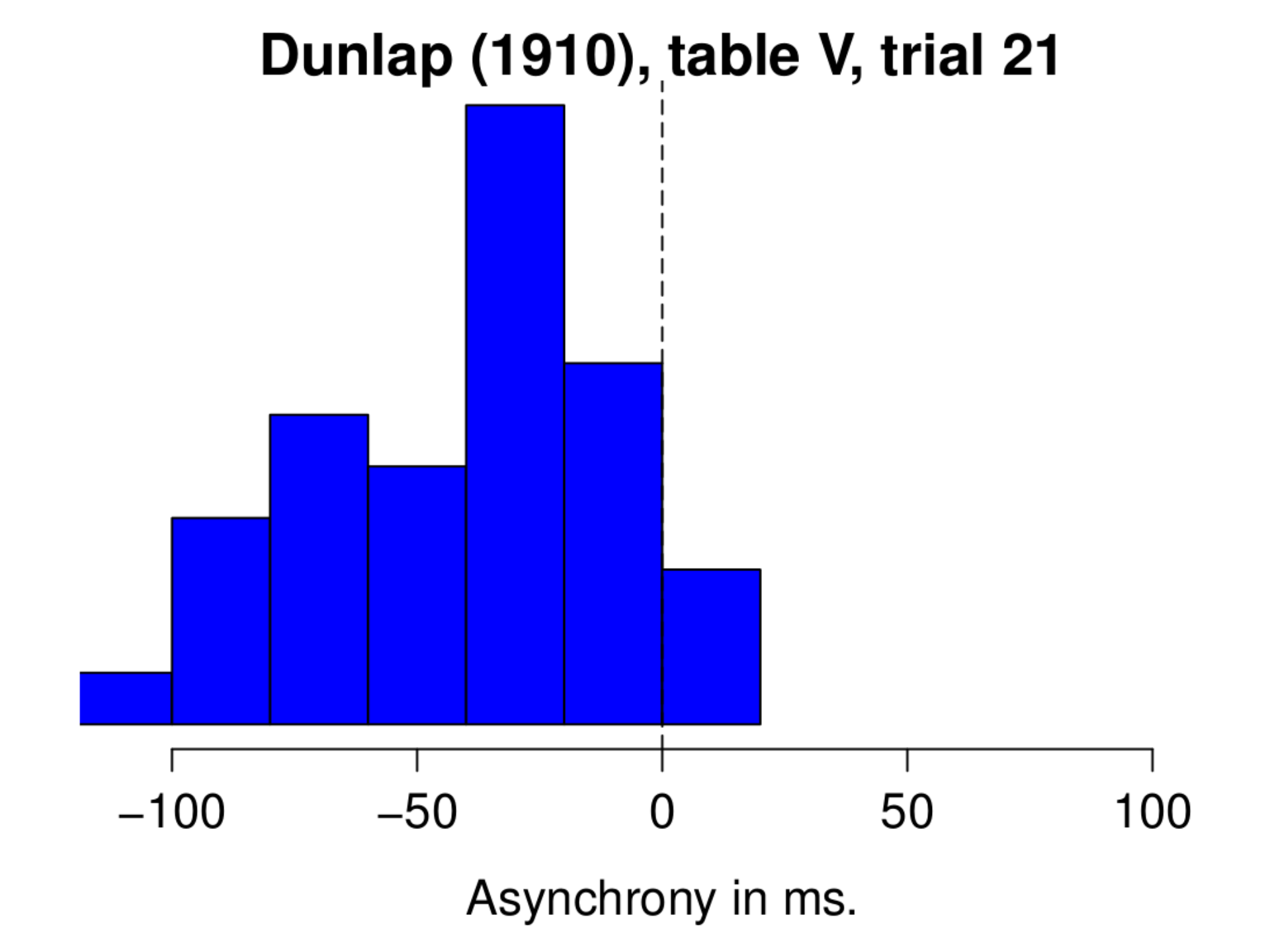
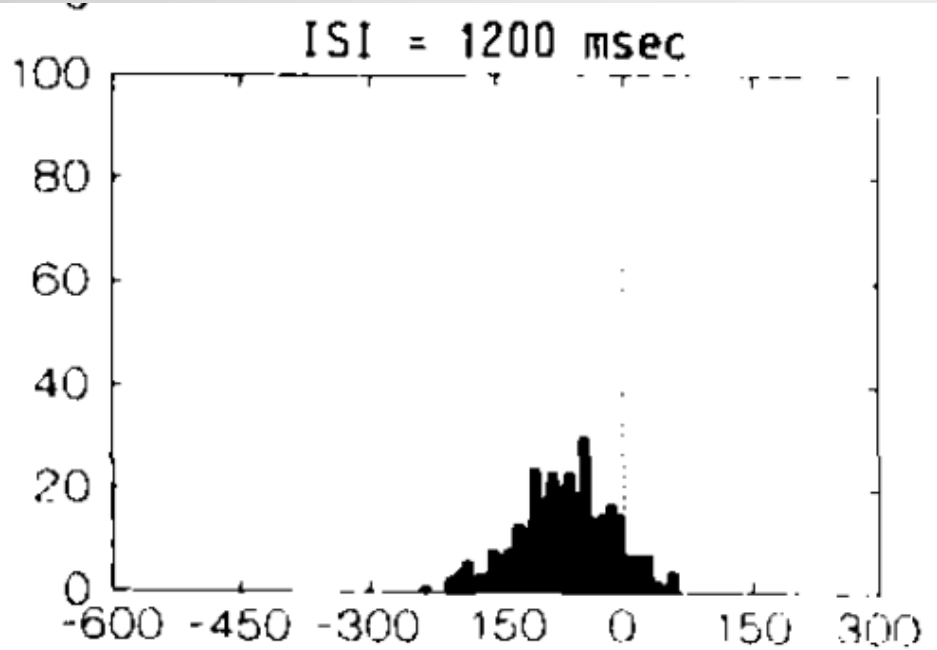
- Asynchronies tend to be normally distributed, **except for when the tapping tempo is slow.**
- A simple model of why the distribution of asynchronies differ depending on the tempo.
- How to accurately estimate the distribution of asynchronies at **any** tempo using Bayesian statistics.

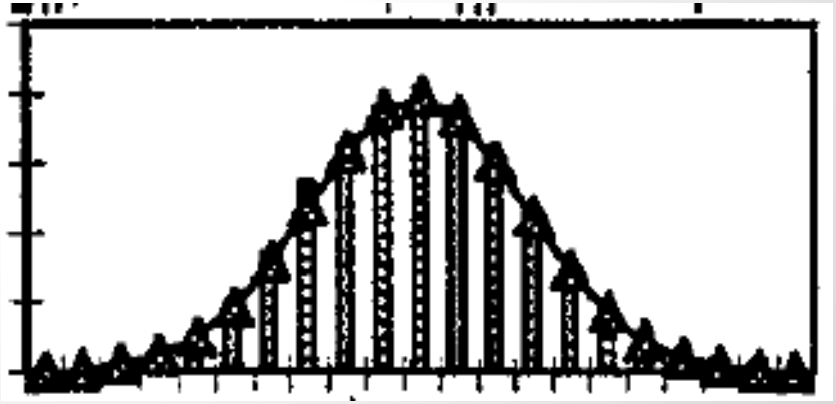
The Distribution of Asynchronies

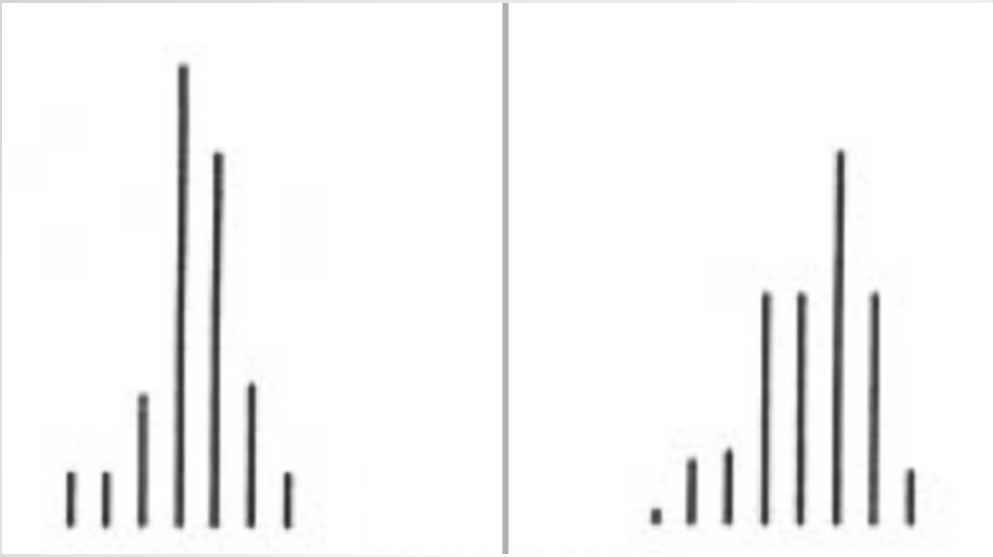

Dunlap (1910), table V, trial 21
−100
−50
0
50
100
Asynchrony in ms.



Mates, J., Müller, U., Radil, T., & Pöppel, E. (1994)

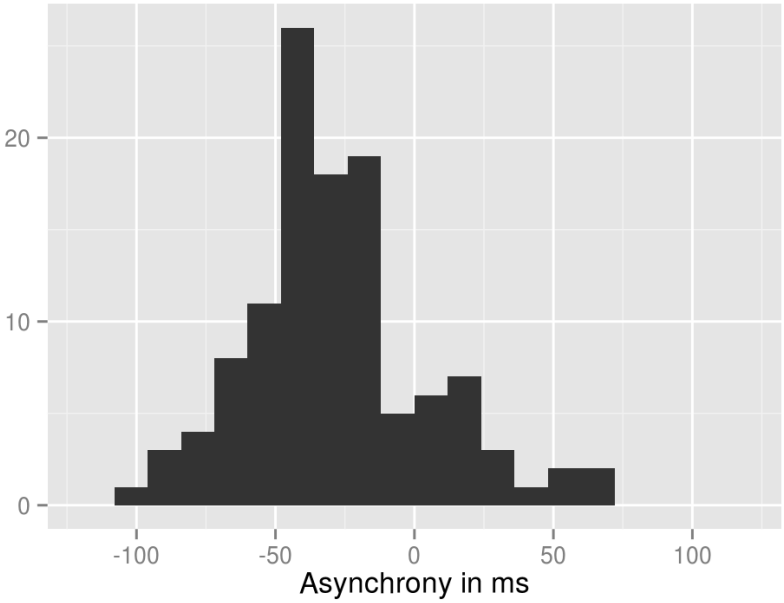
Chen, Ding & Kelso (1997)

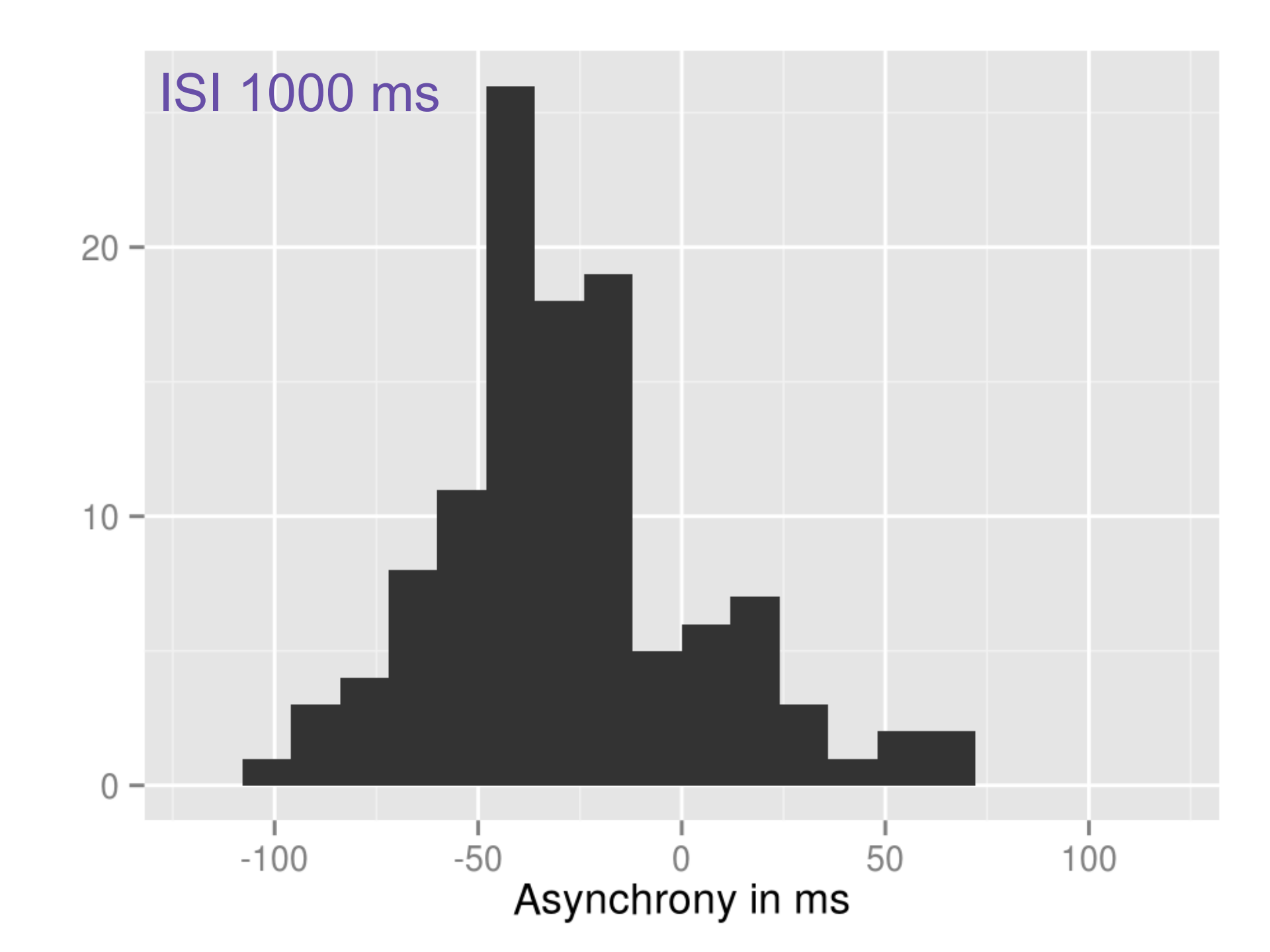


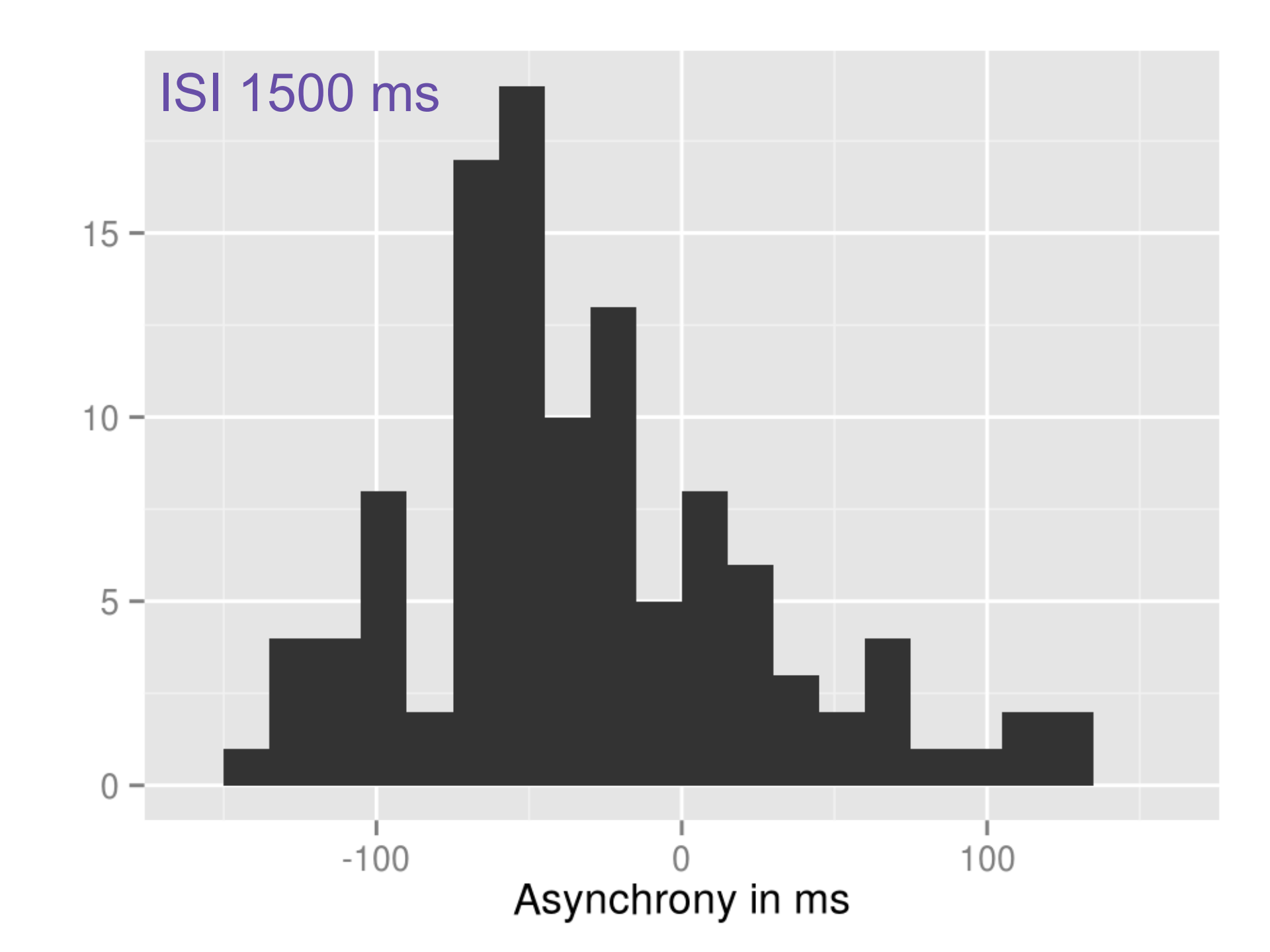


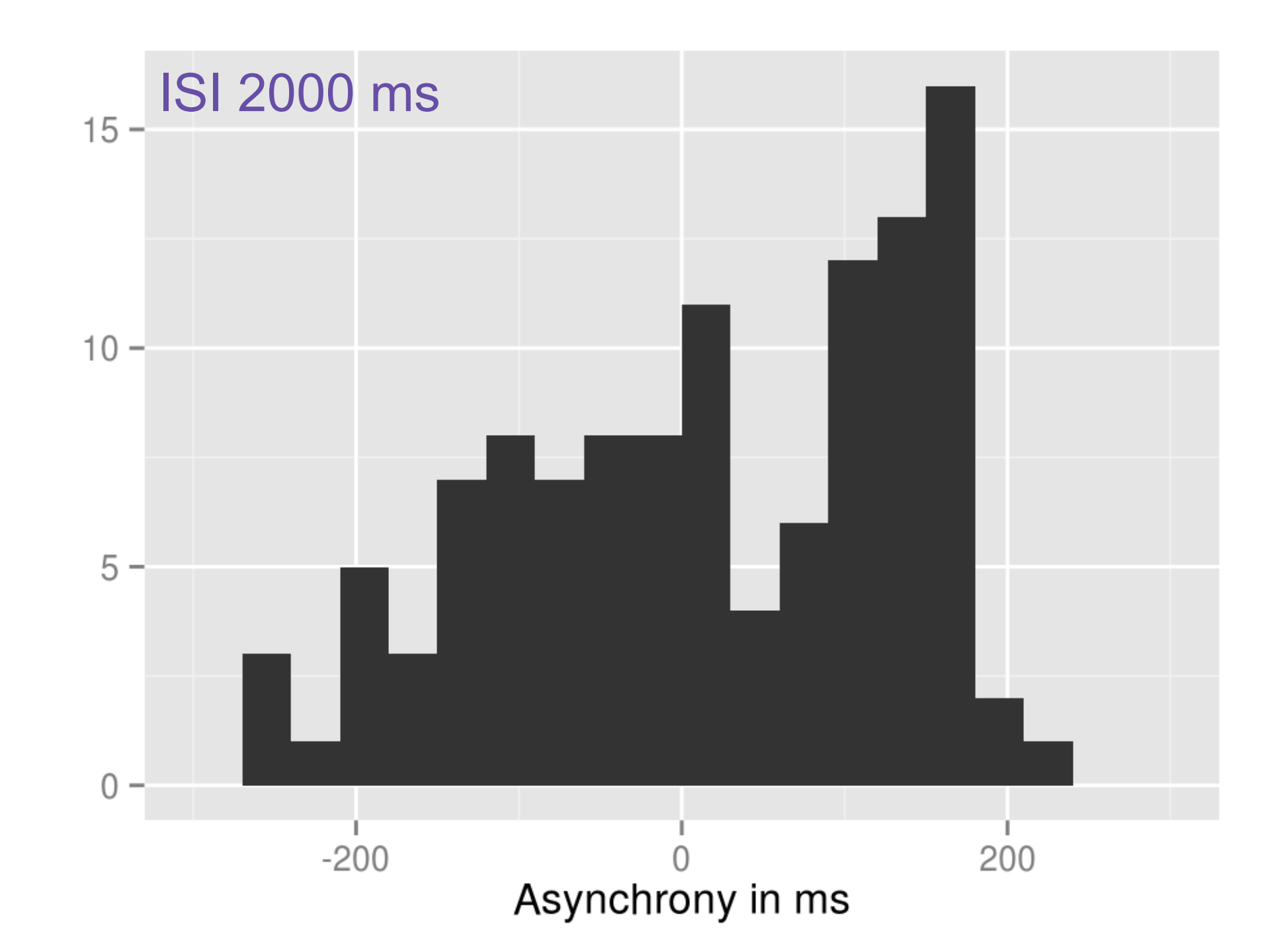
Moore, G. P., & Chen, J. (2010).

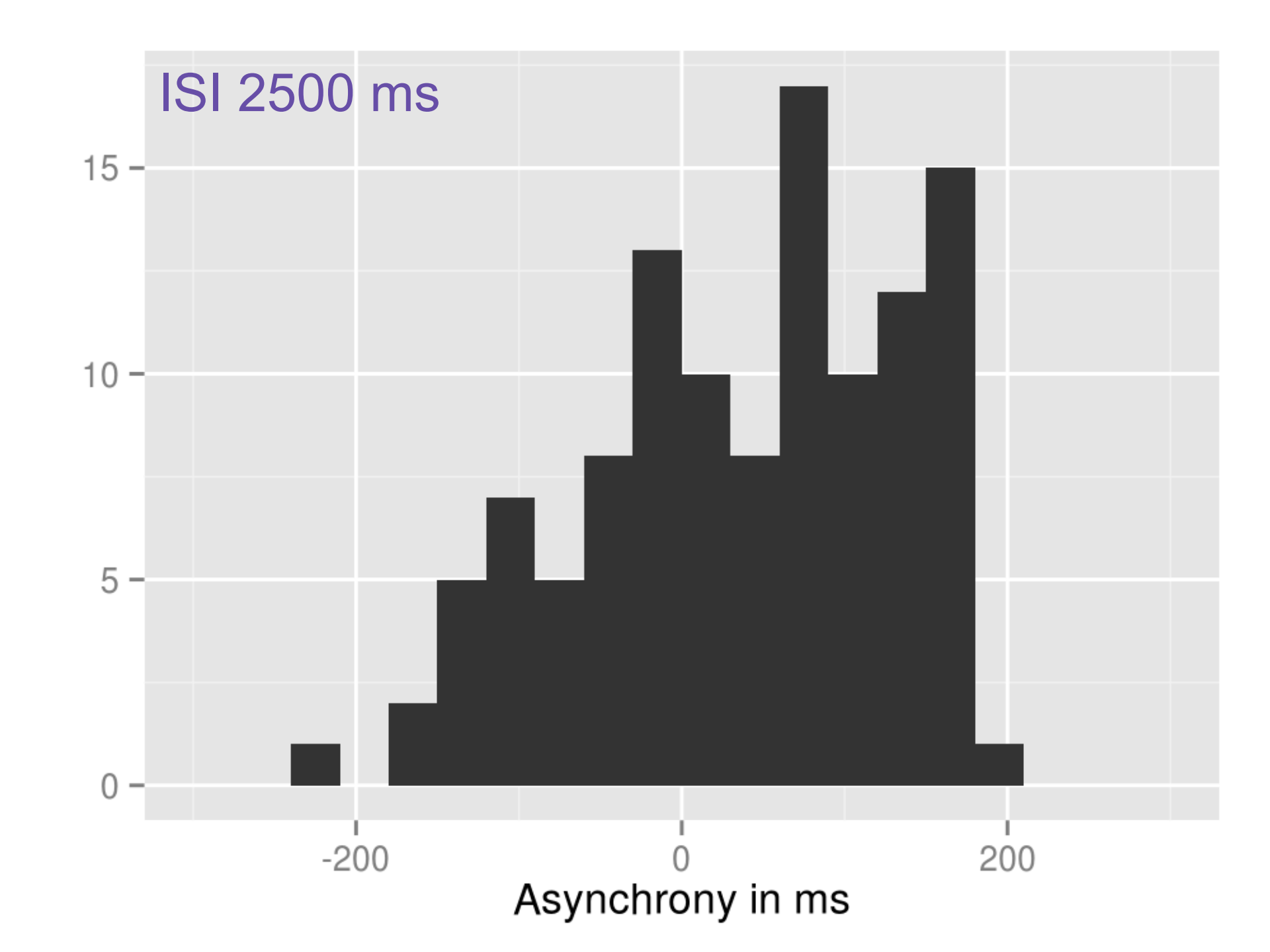
Repp, B. H., & Doggett, R. (2007)

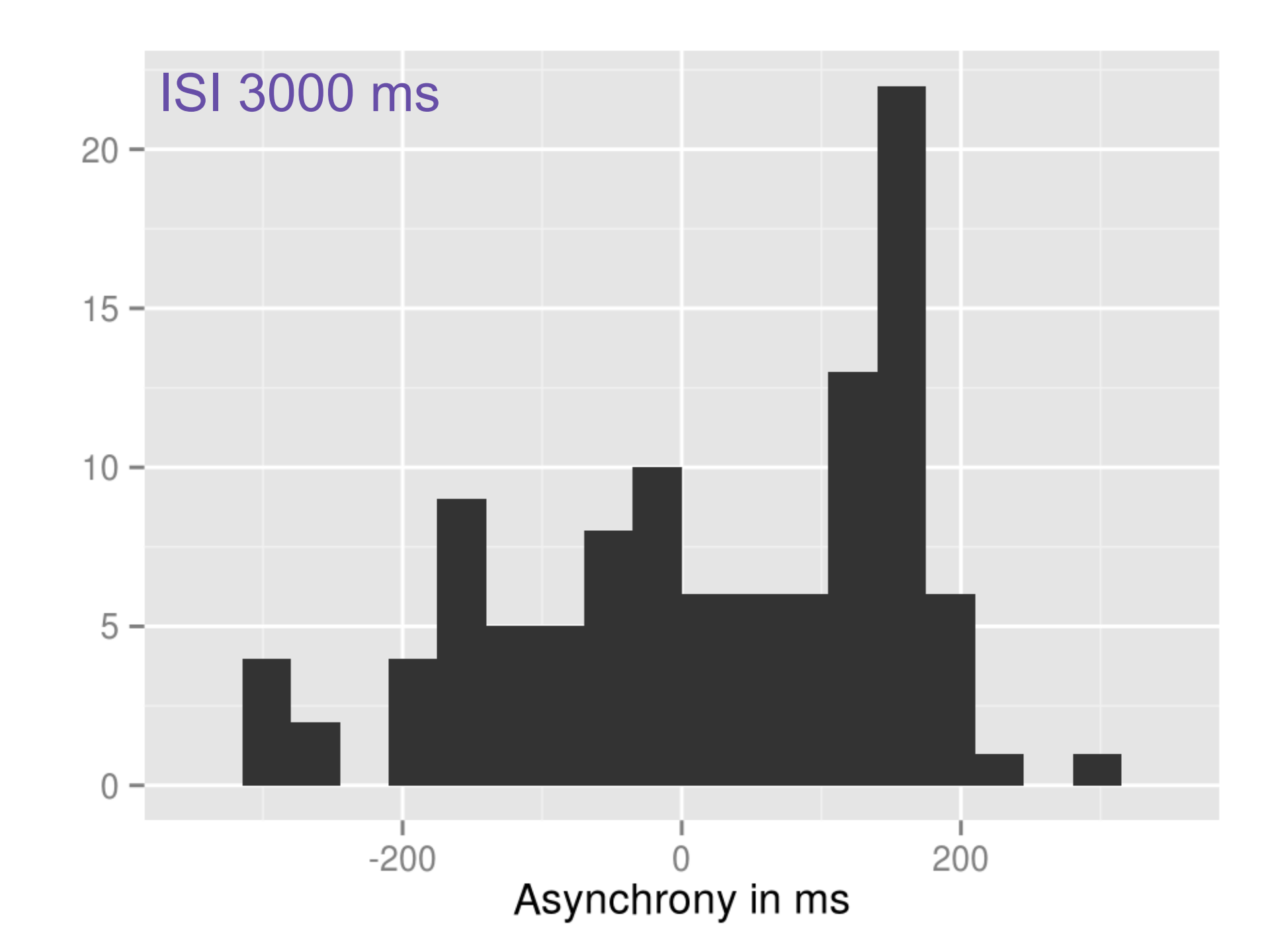


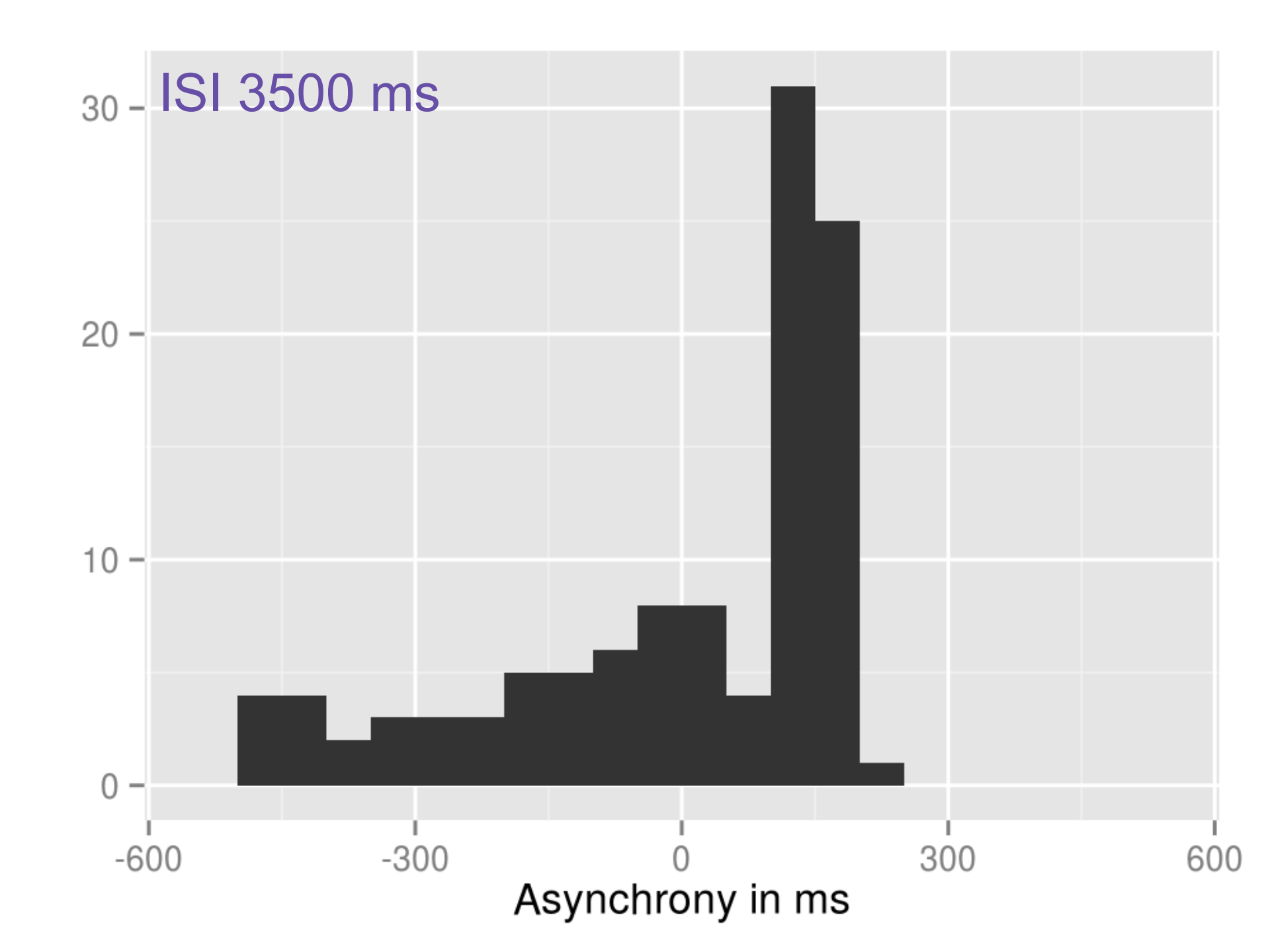

ISI 1000 ms
20
10
0
-100
-50
0
50
100
Asynchrony in ms


ISI 1500 ms
15
10
5
0
-100
0
100
Asynchrony in ms

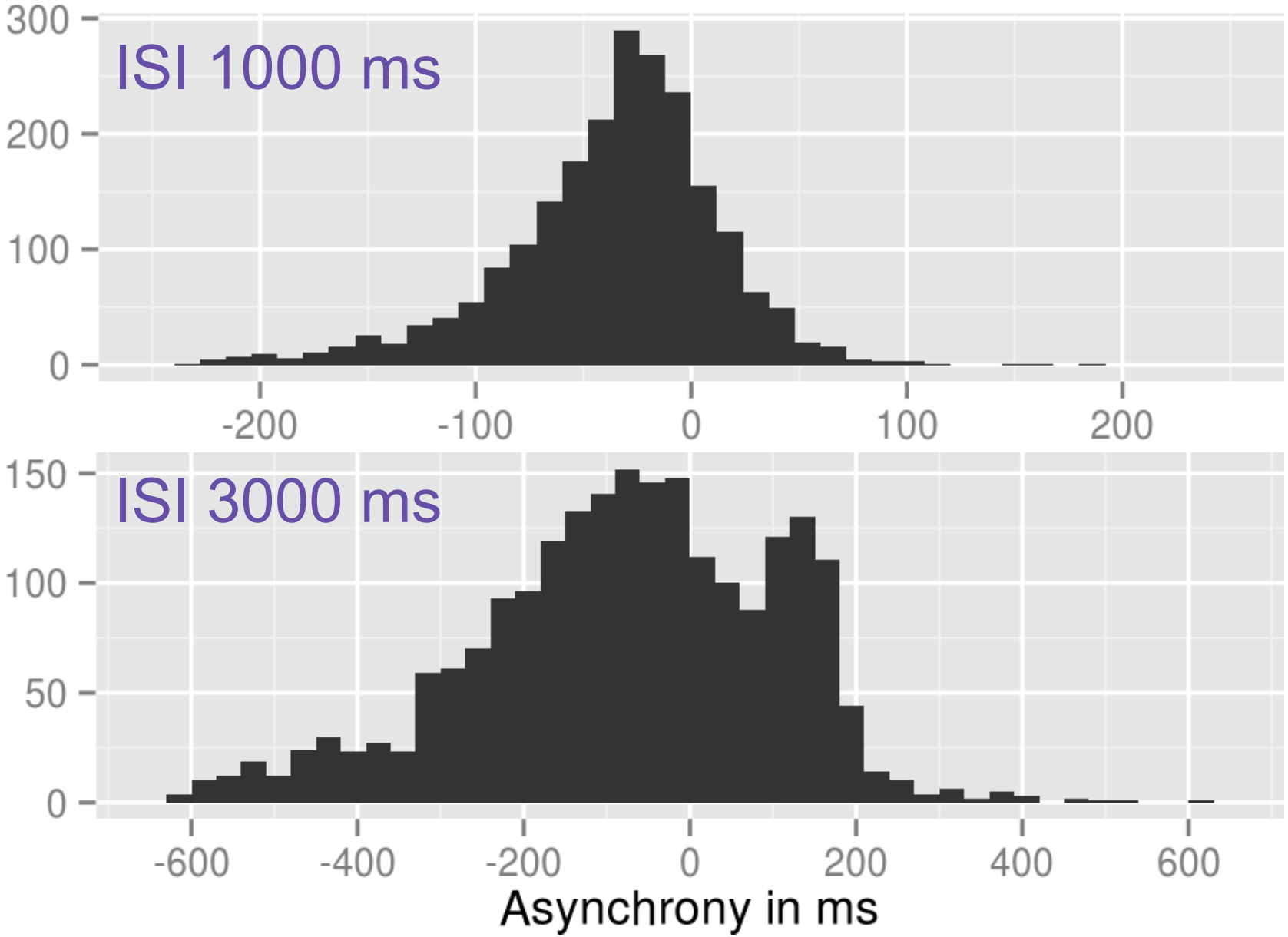

ISI 2000 ms
15
10
5
0
-200
0
200
Asynchrony in ms


ISI 2500 ms
15
10
5
0
-200
0
200
Asynchrony in ms

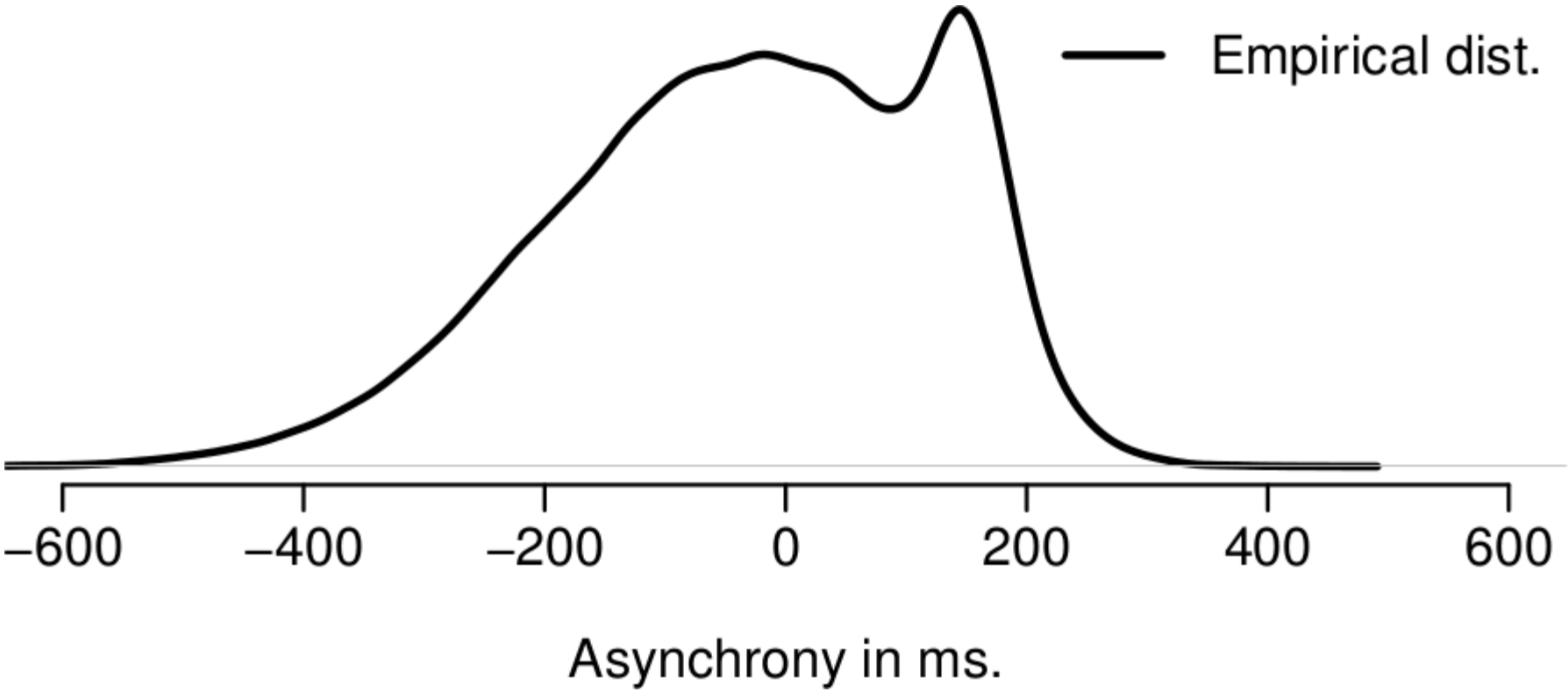

ISI 3000 ms
20
15
10
5
0
-200
0
200
Asynchrony in ms

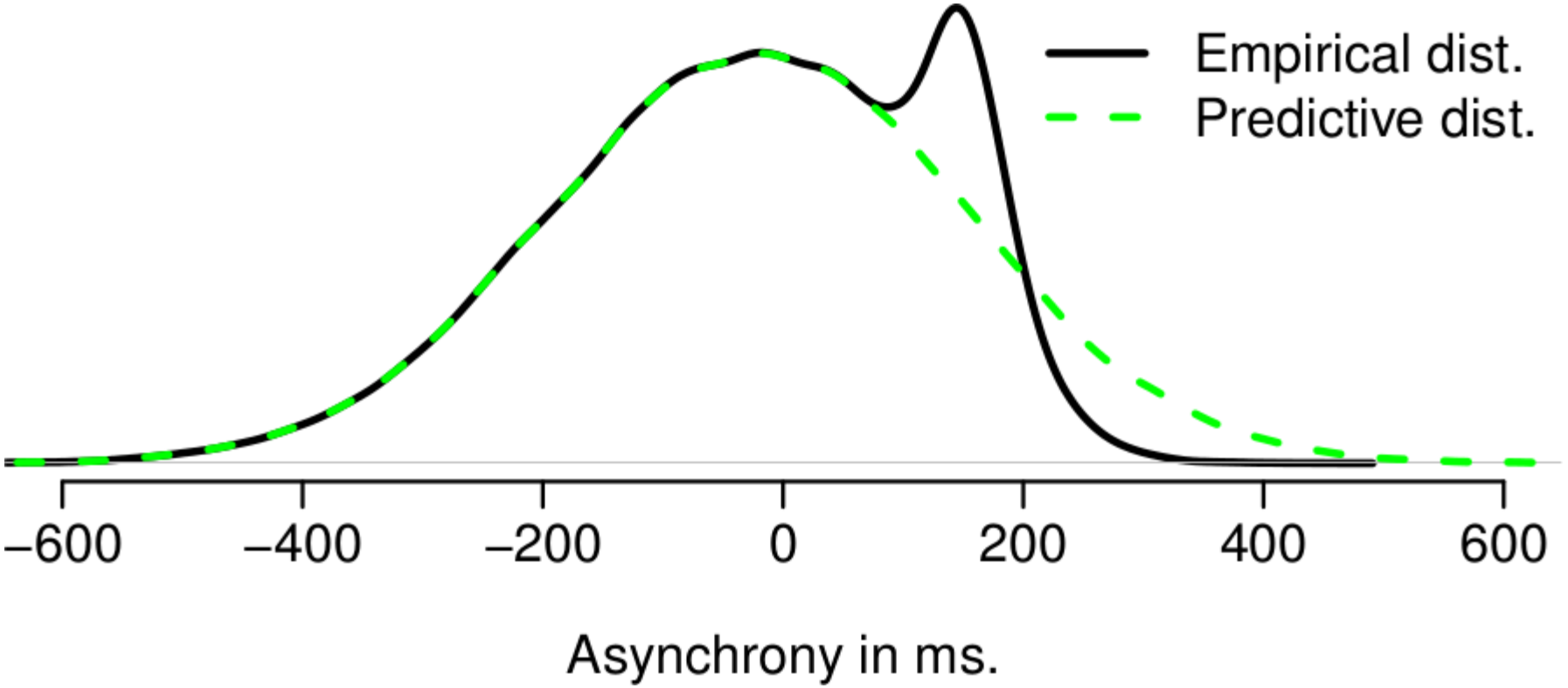

ISI 3500 ms
30
20
10
0
-600
-300
0
300
600
Asynchrony in ms

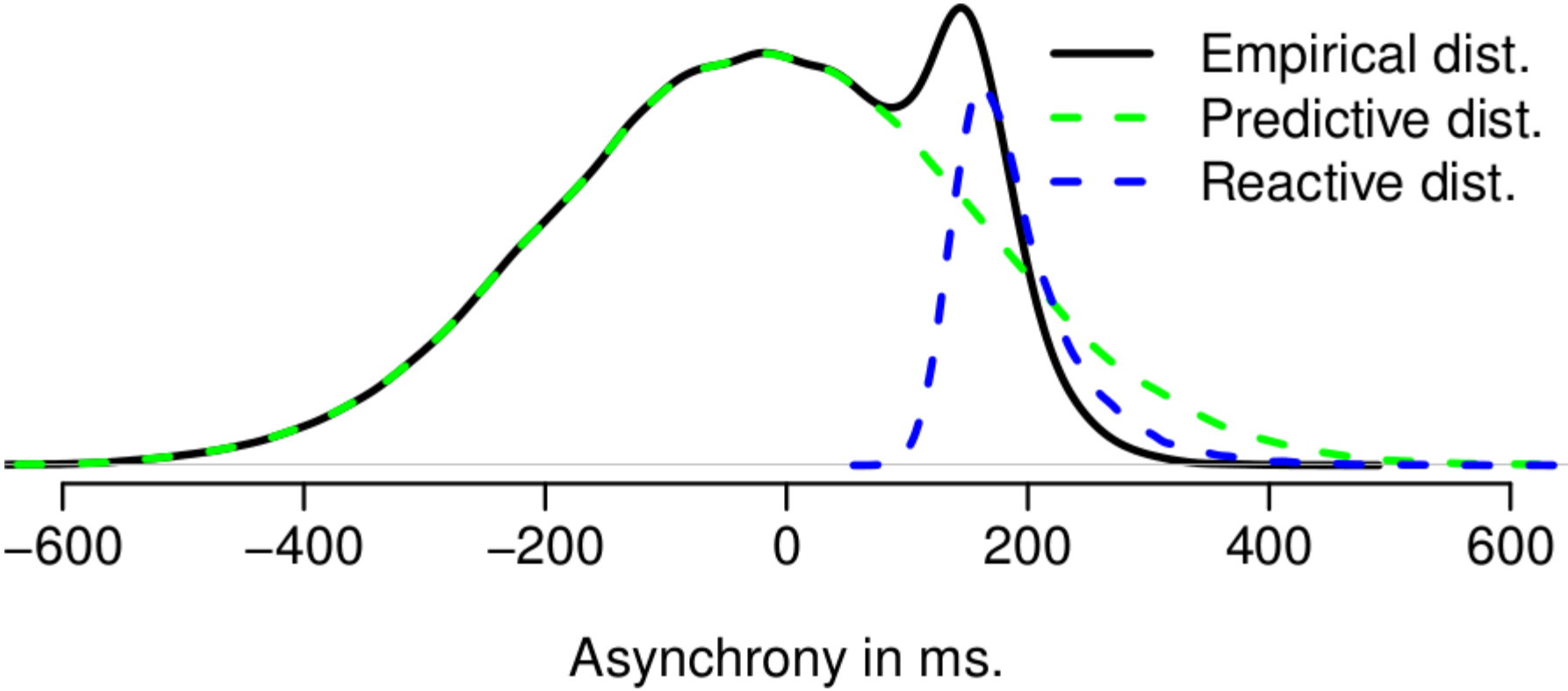
All 18 participants in Repp & Doggett

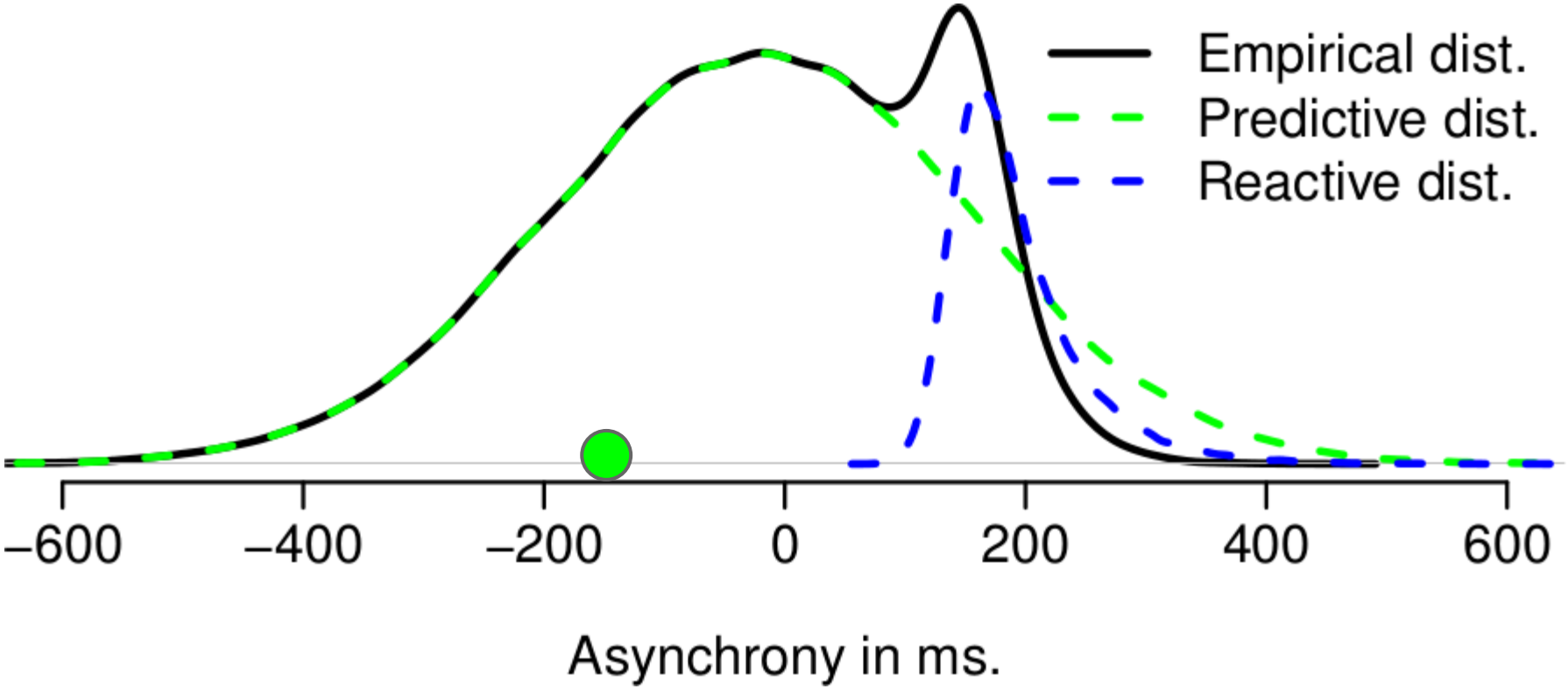


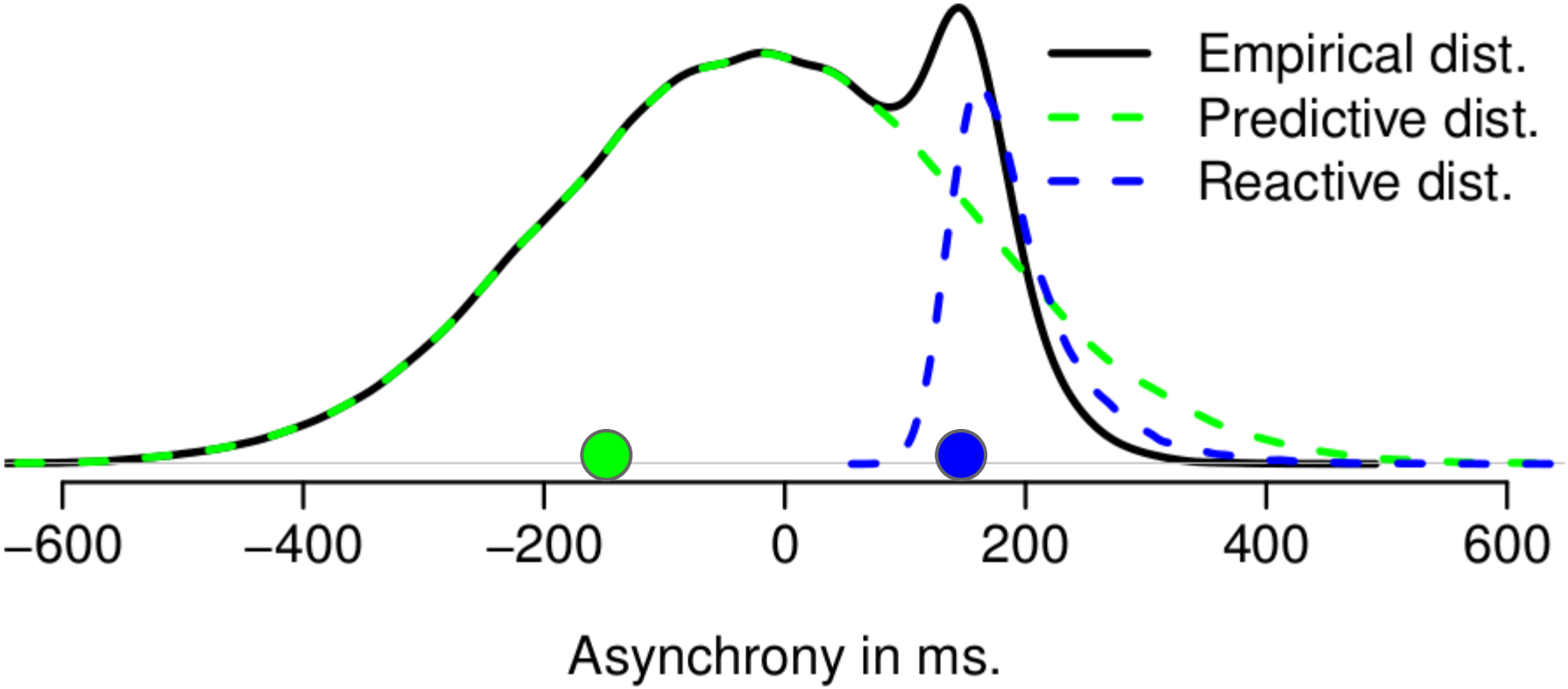
A model of why the distribution of asynchronies differ depending on the tempo.

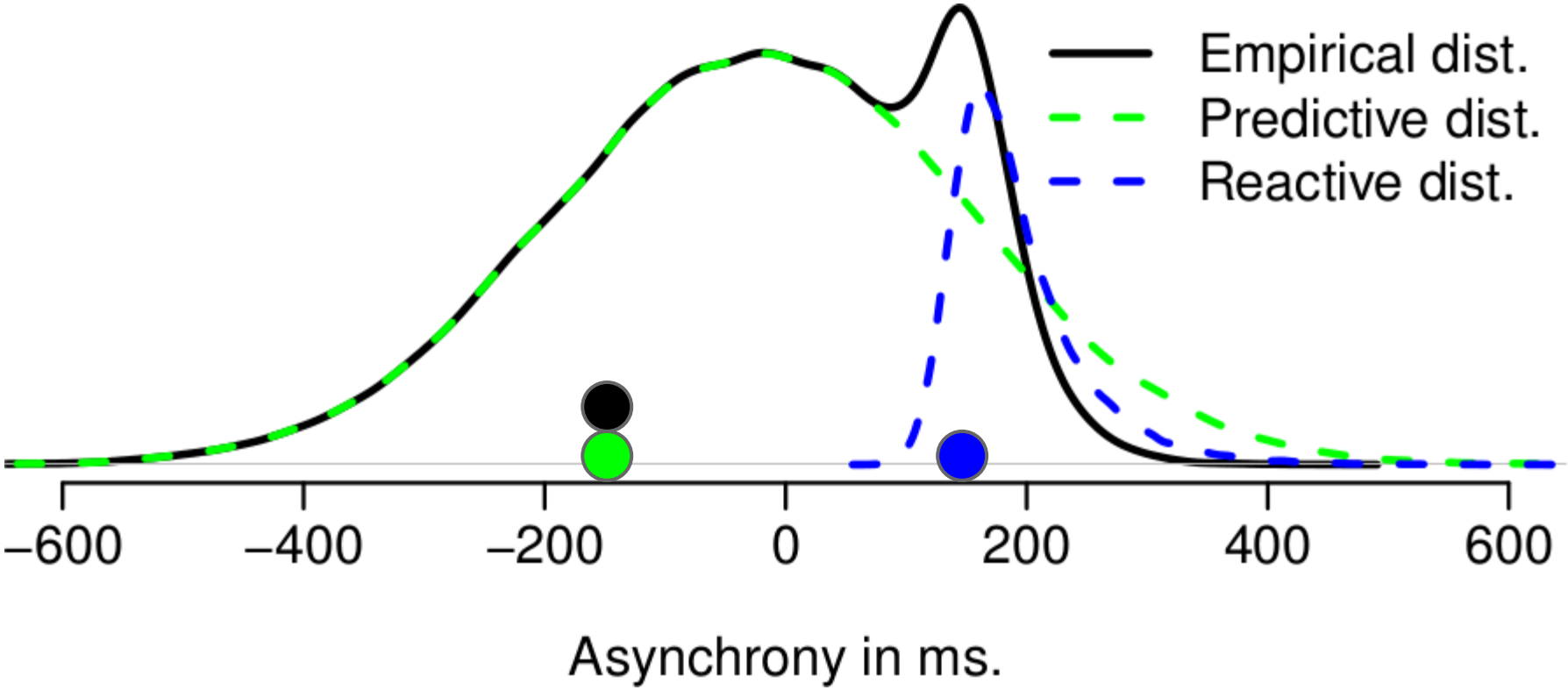

Empirical dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

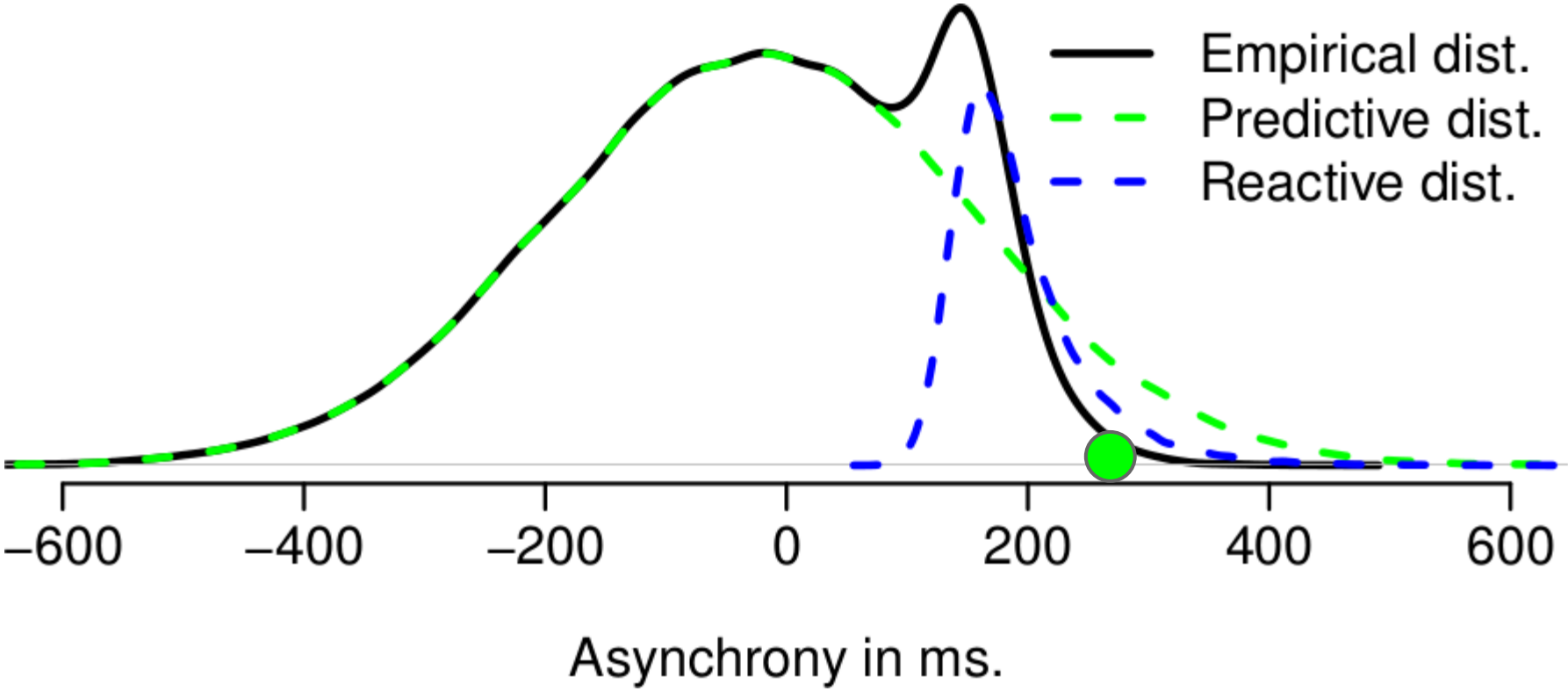

Empirical dist.
Predictive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

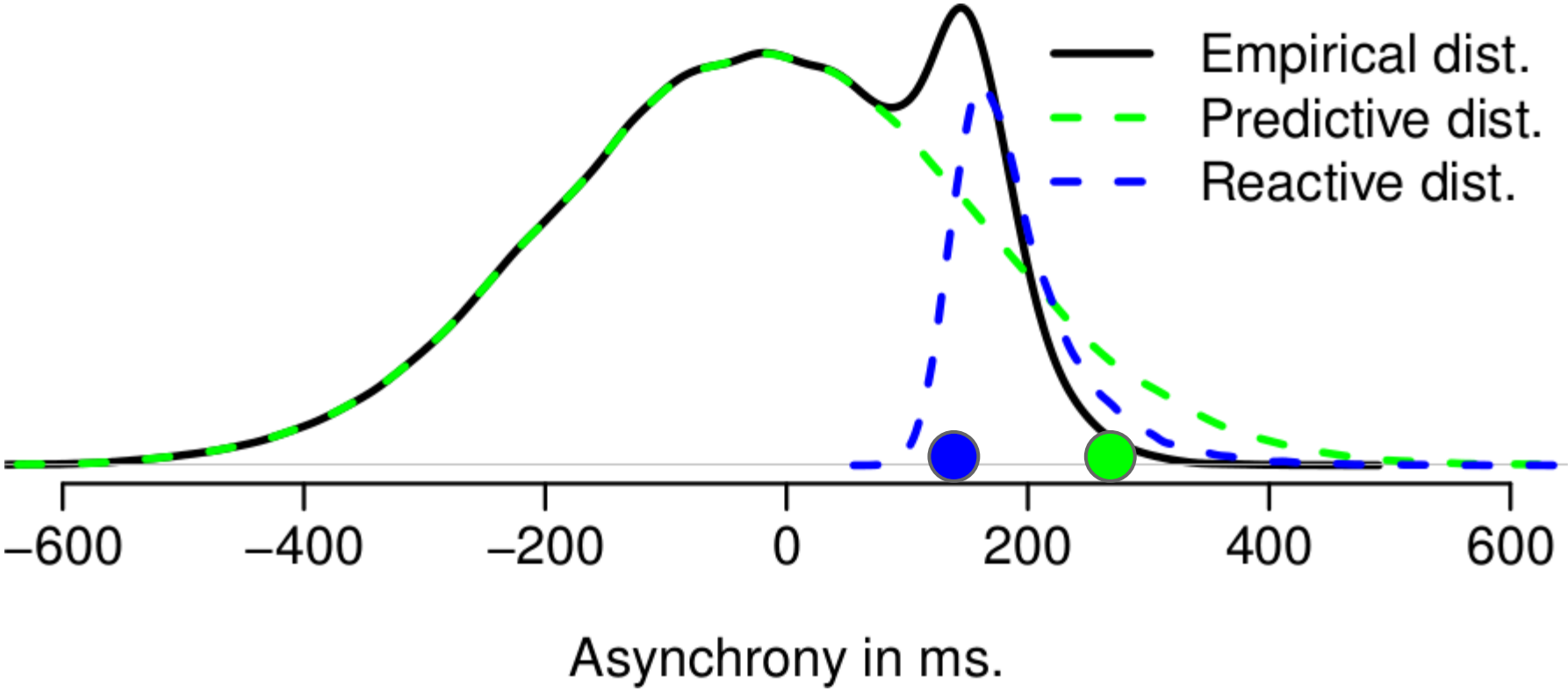

Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

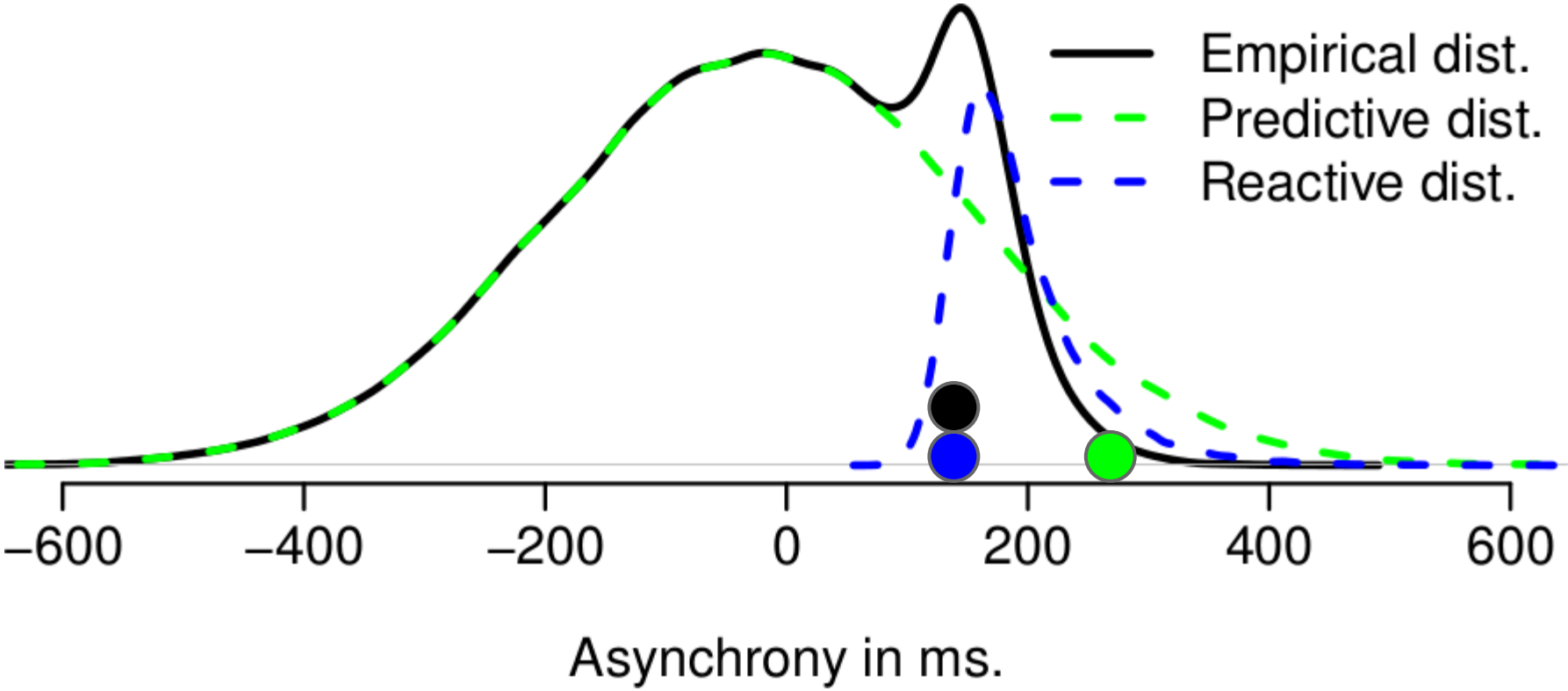

Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

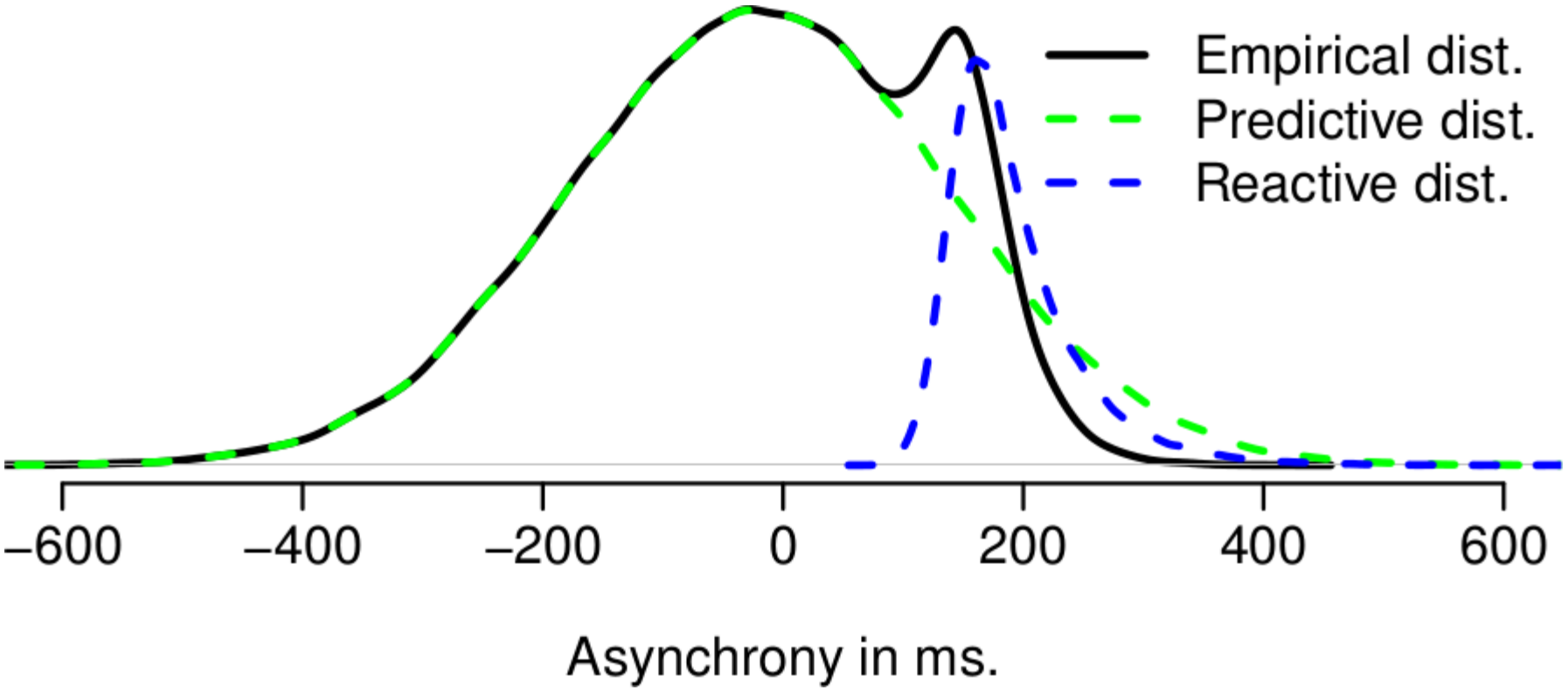

Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

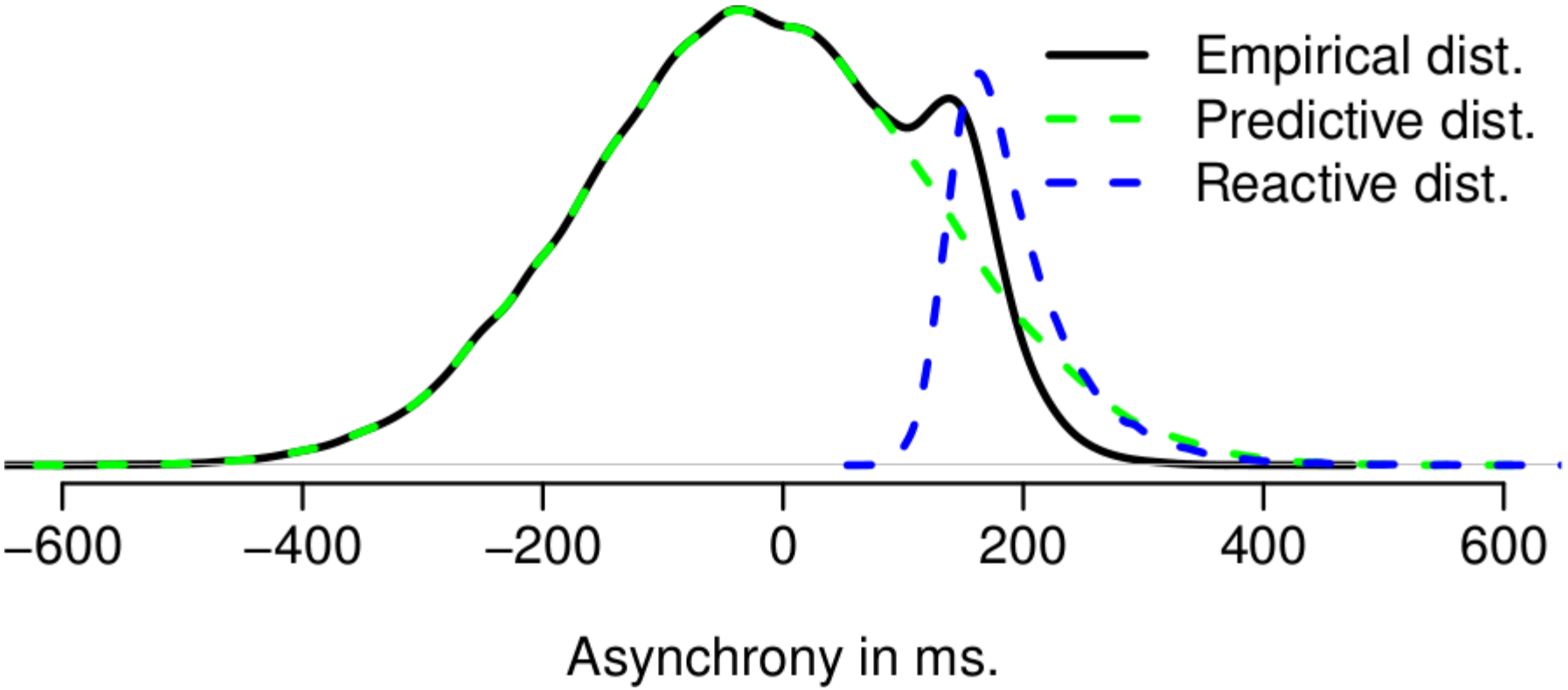

Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

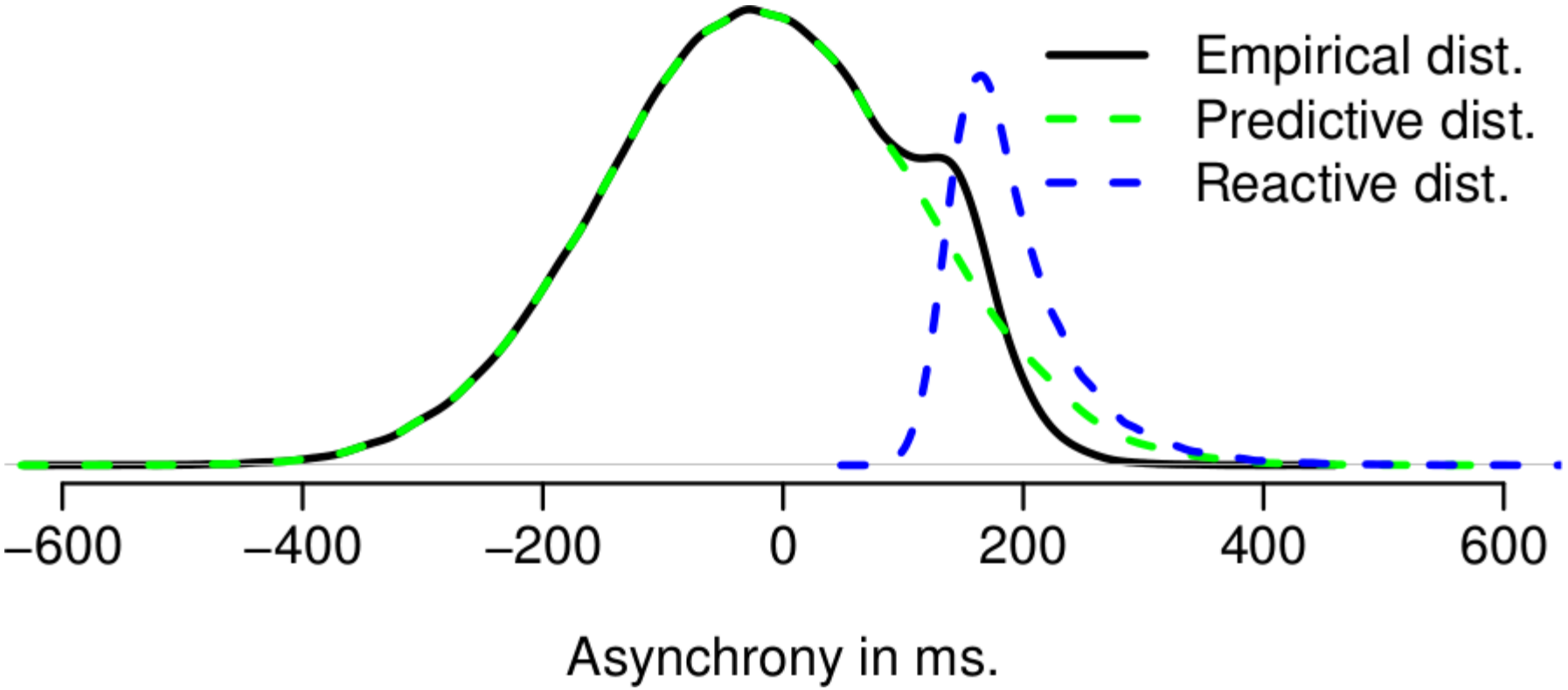

Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

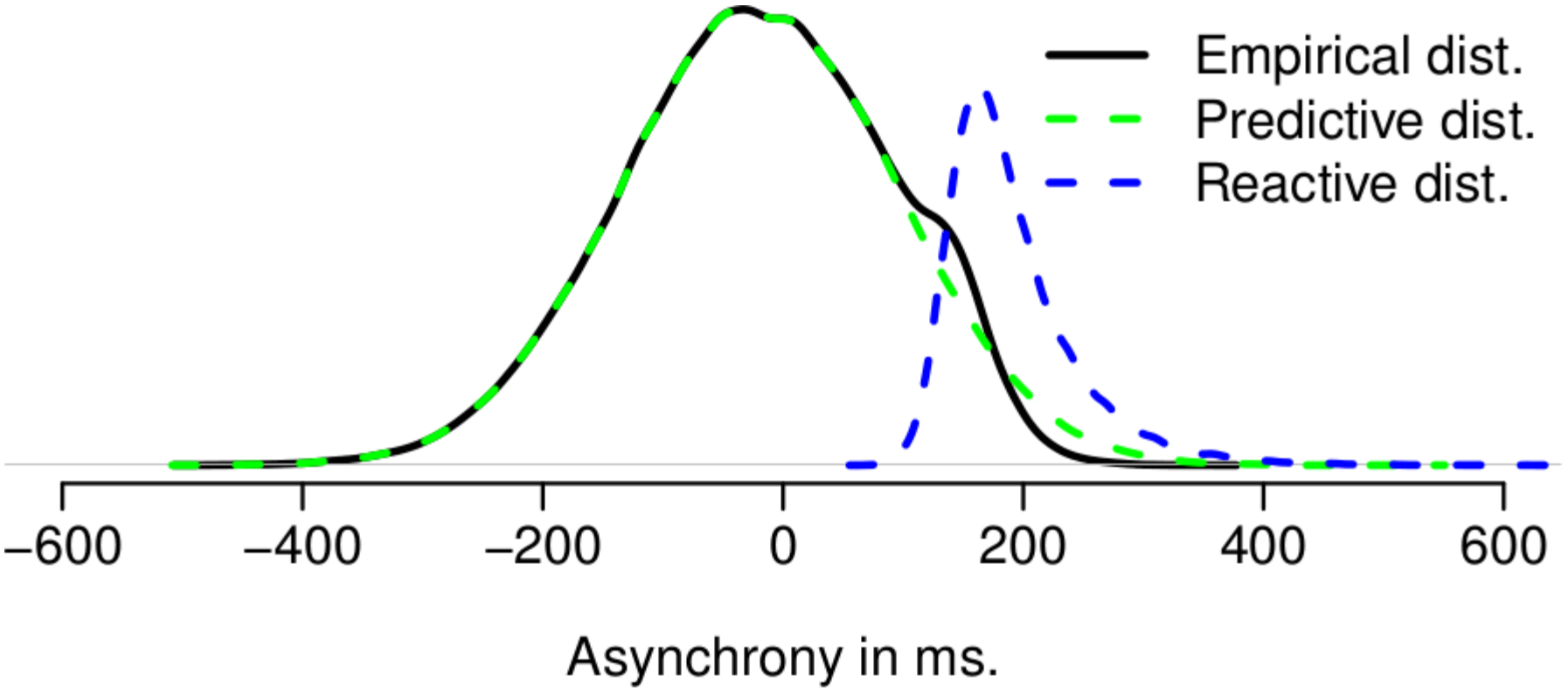

Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
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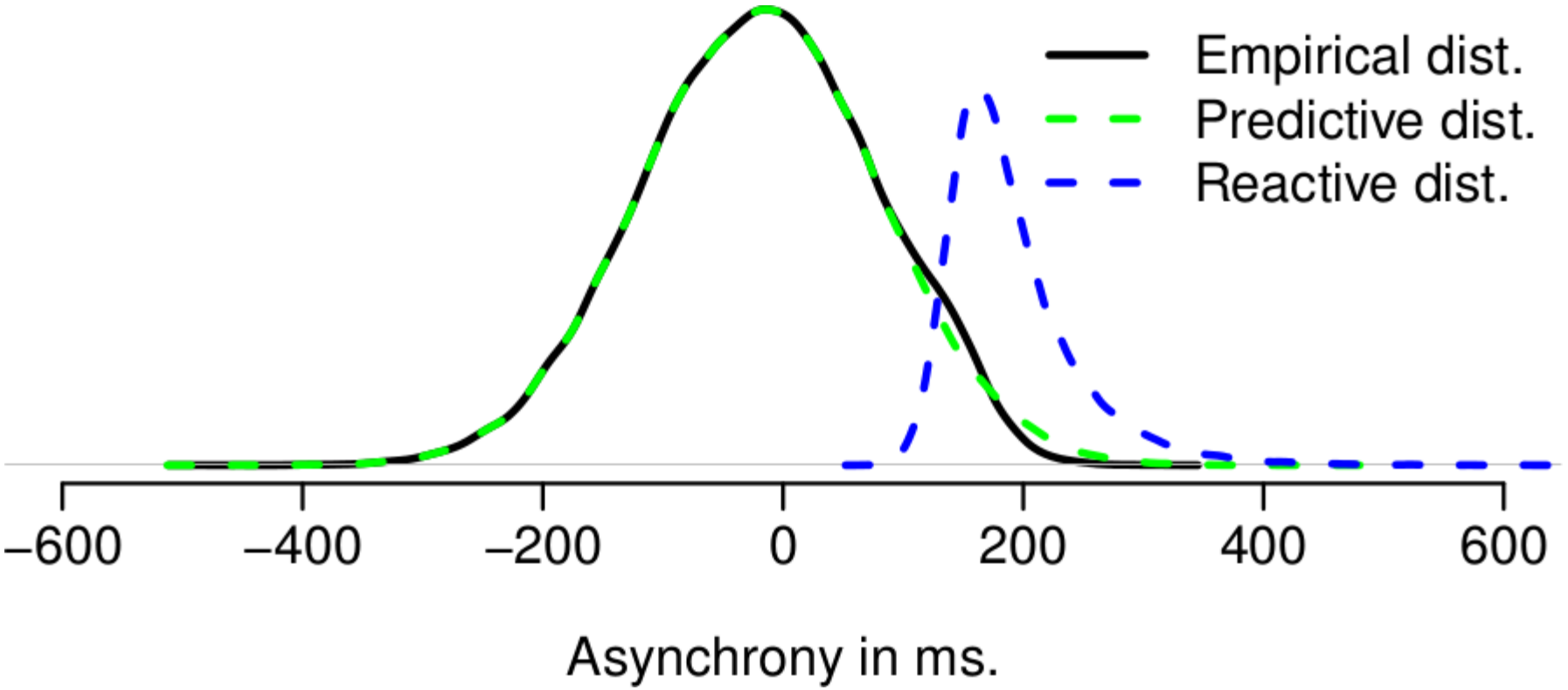
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
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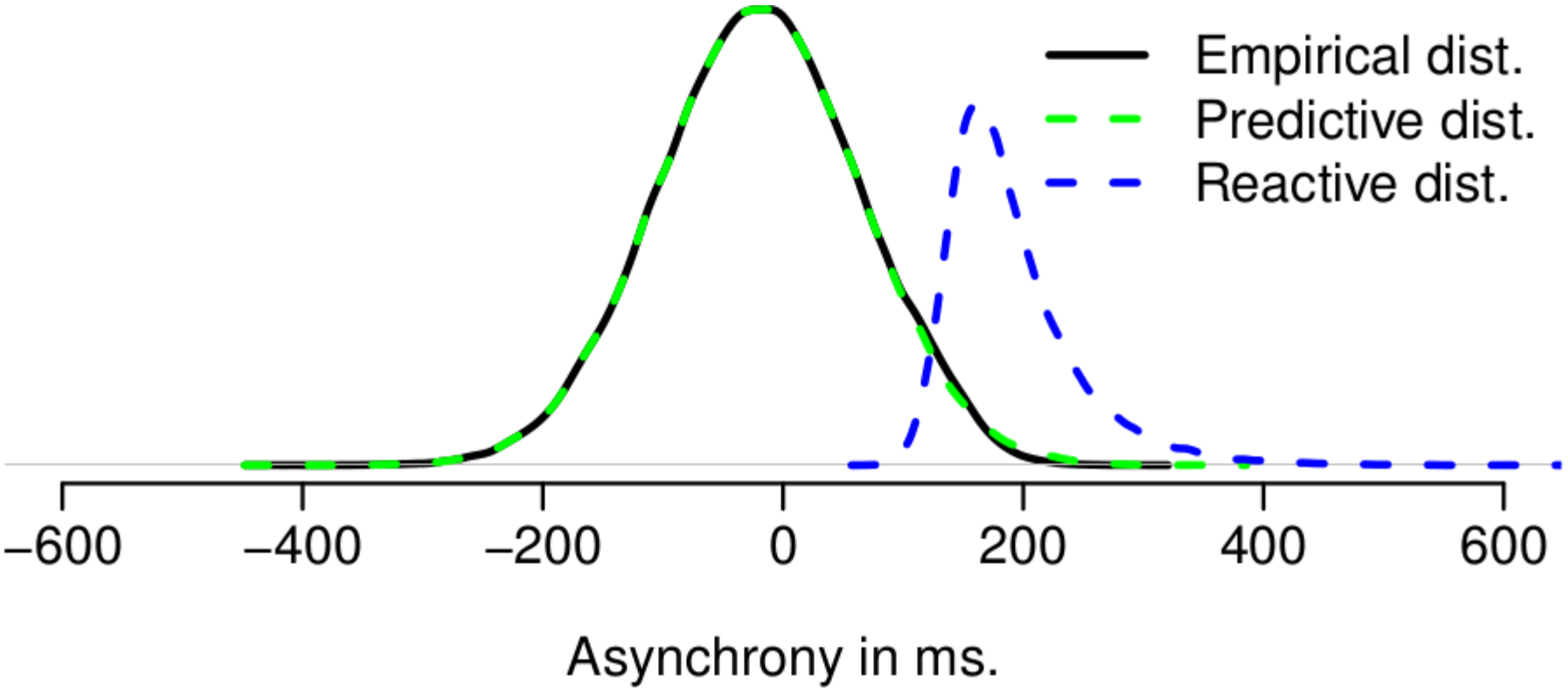
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
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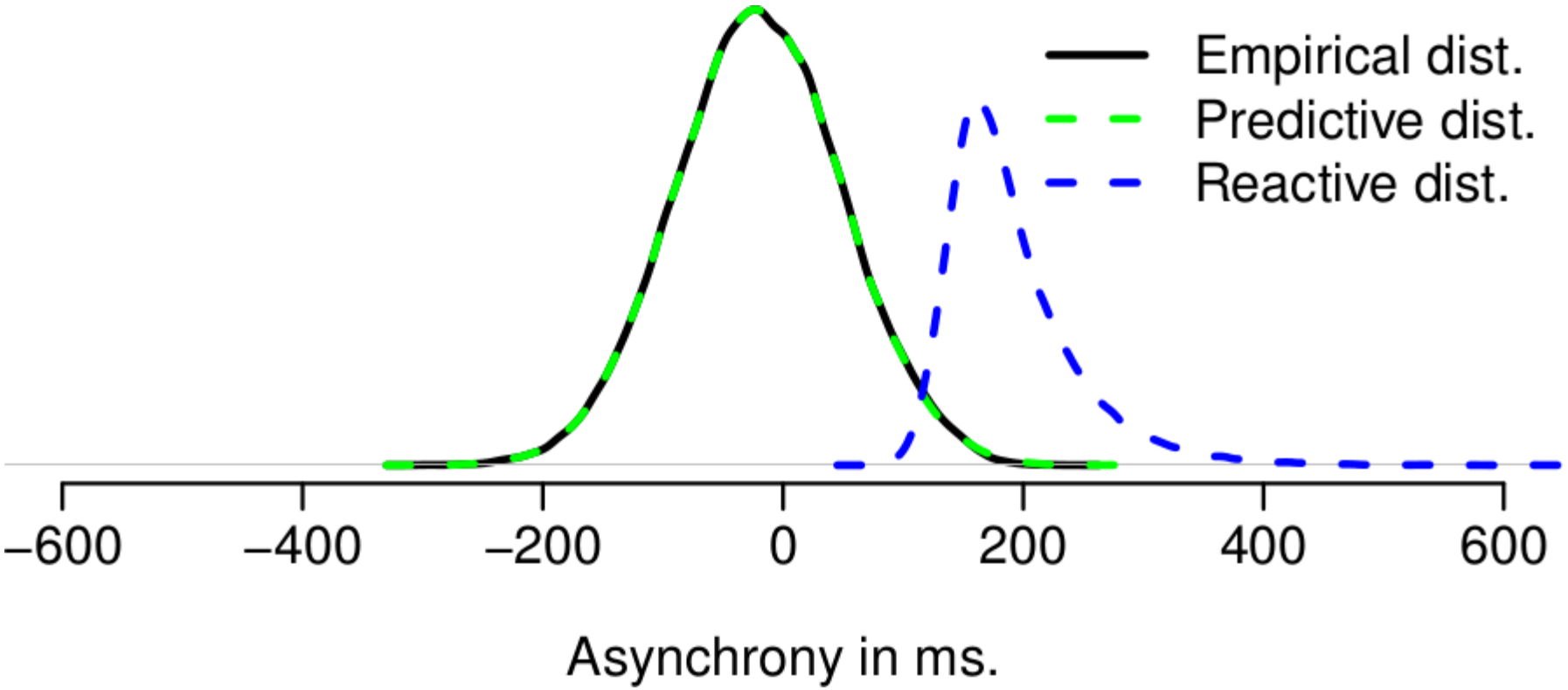
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
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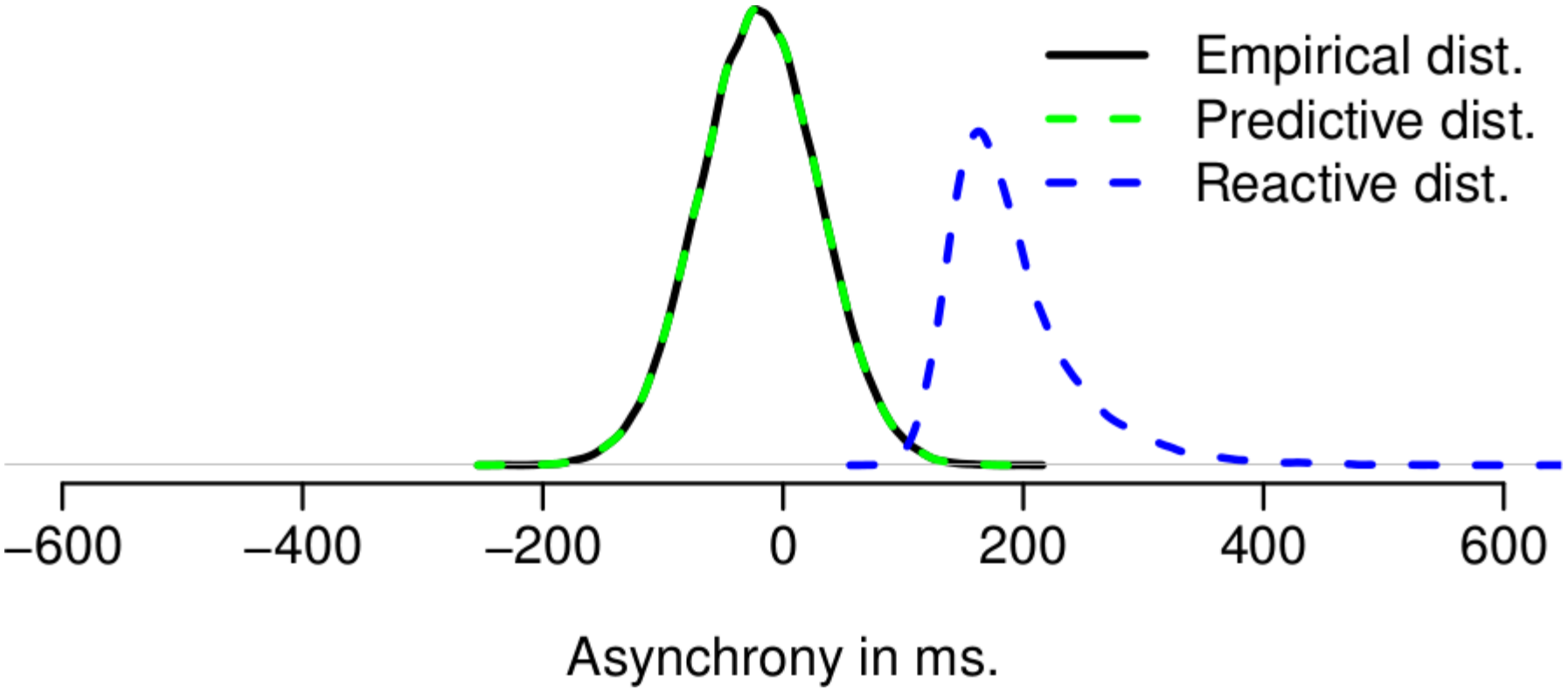
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
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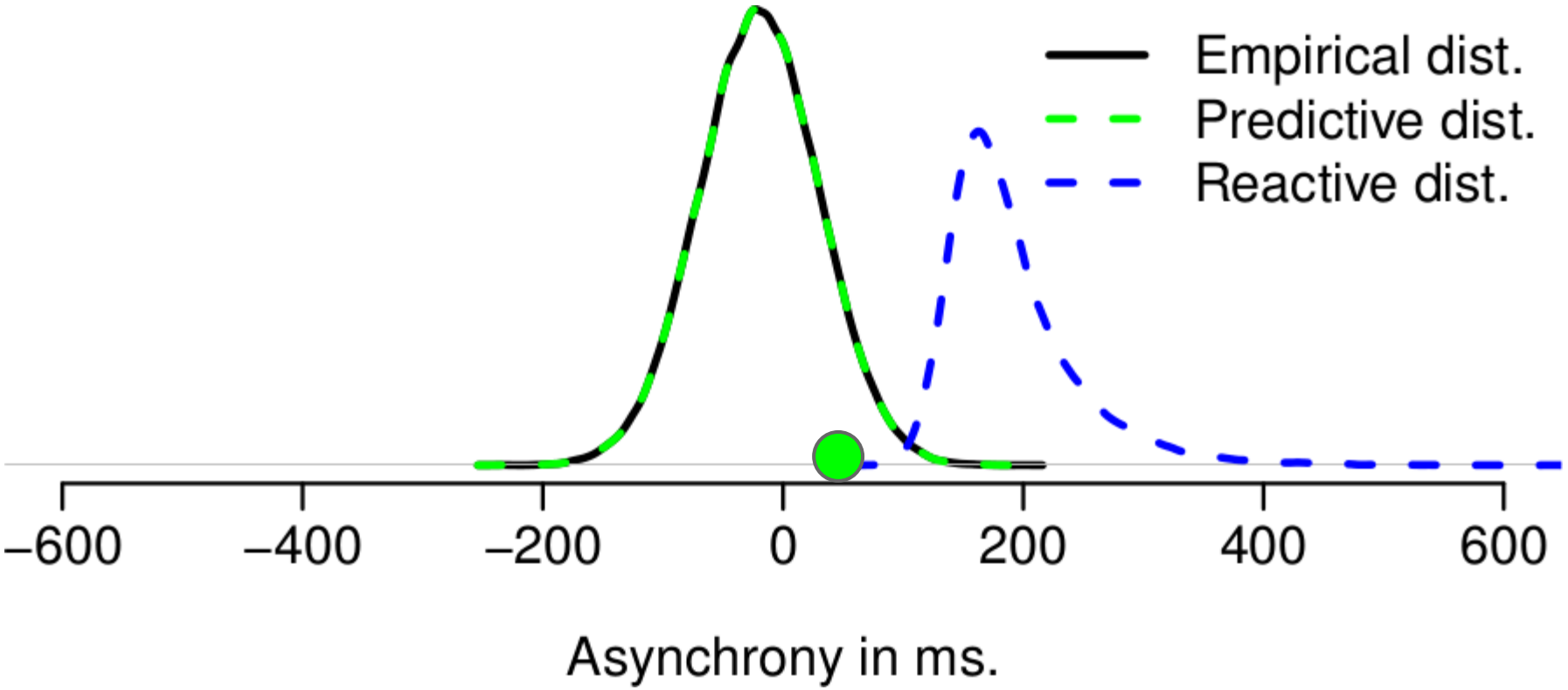
400
600
Asynchrony in ms.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Reactive dist.
−600
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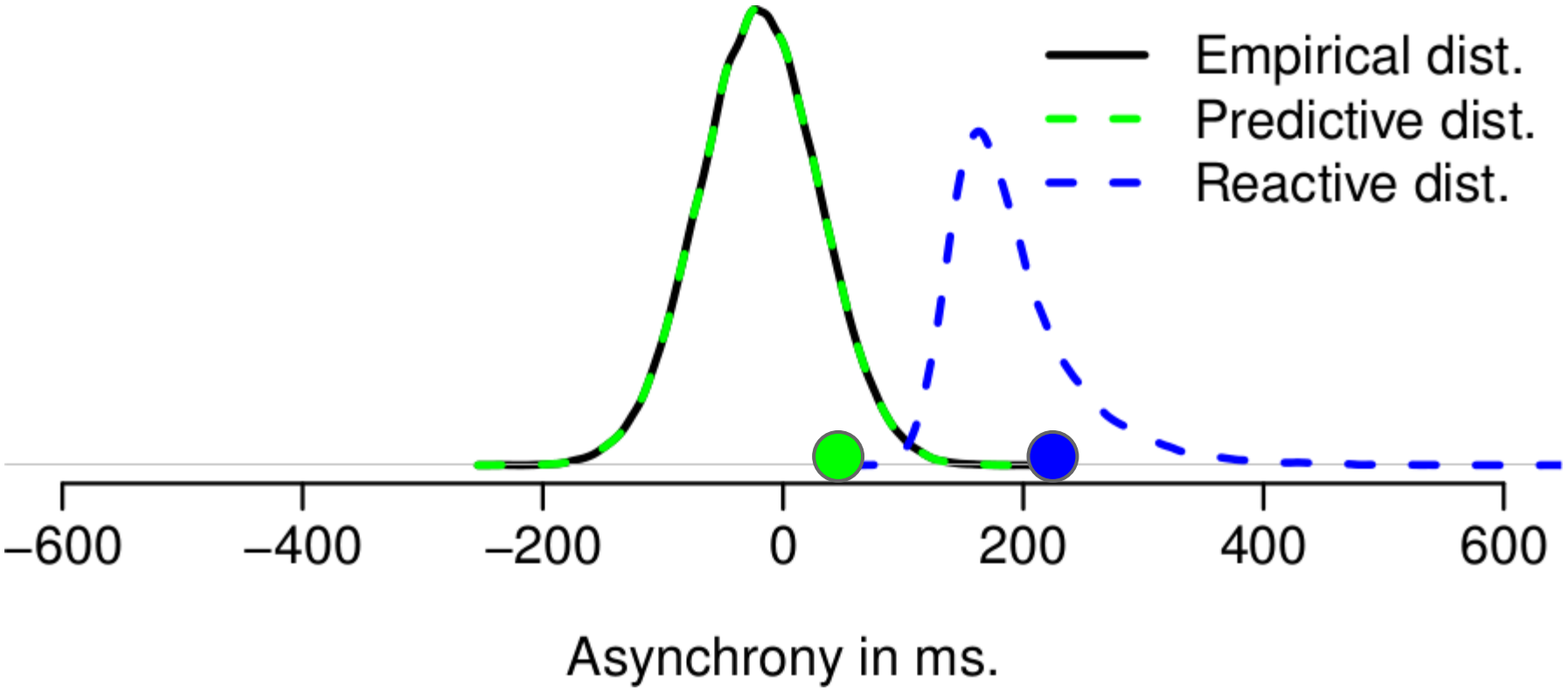
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
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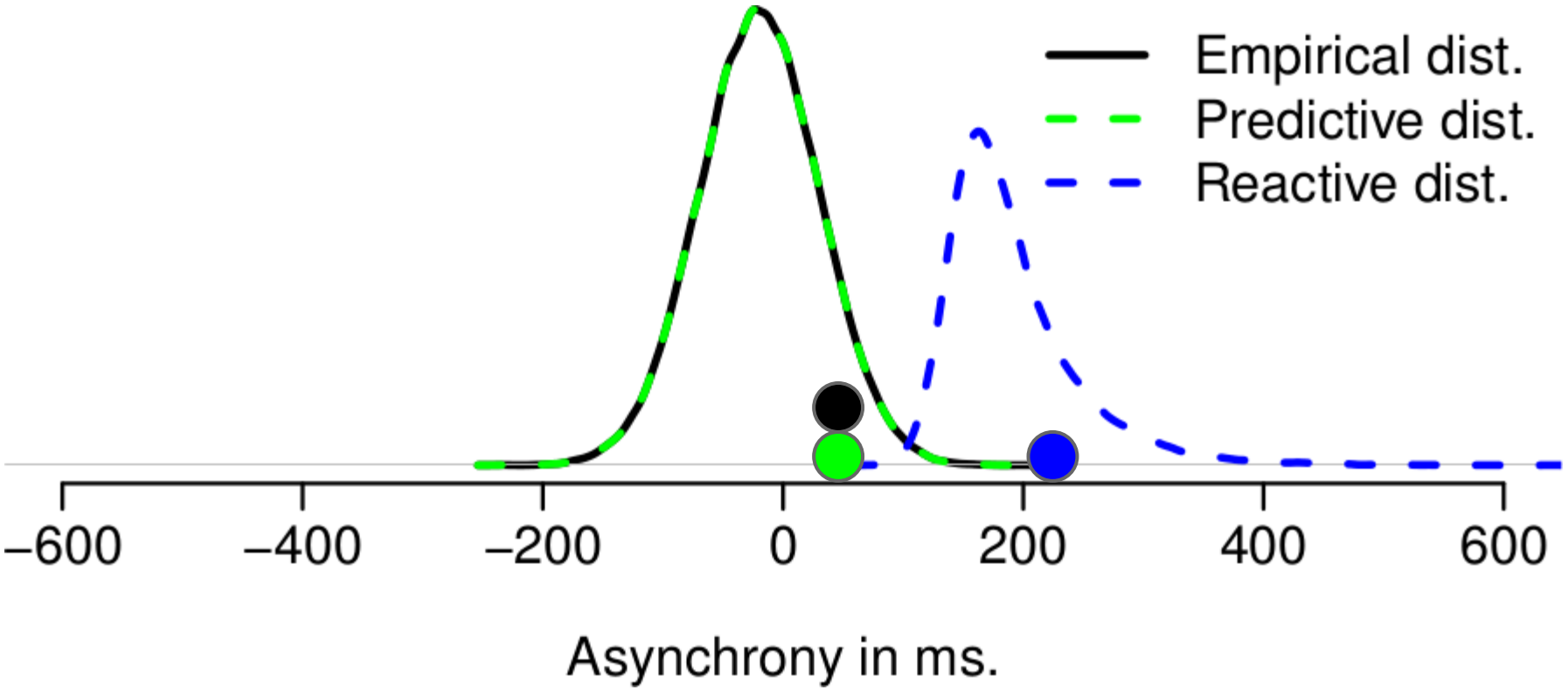
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
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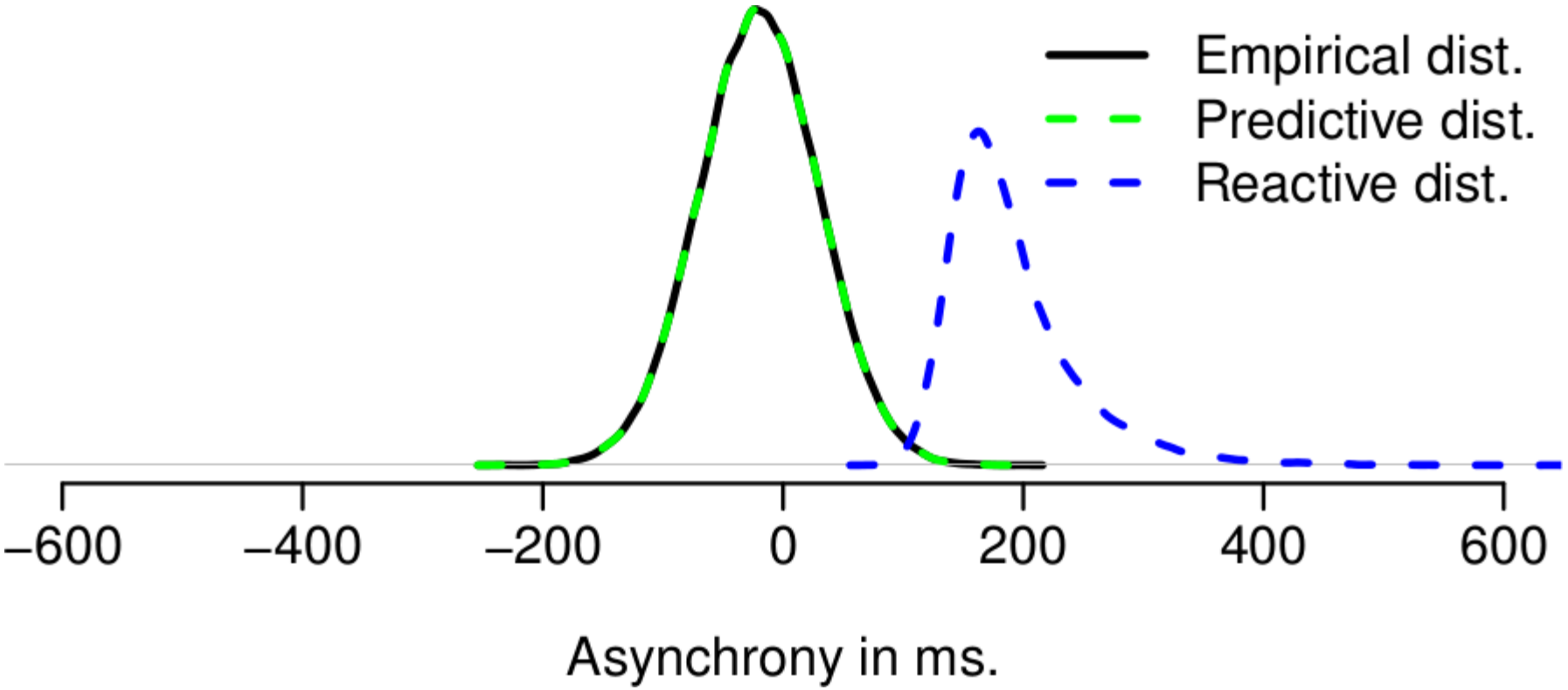
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
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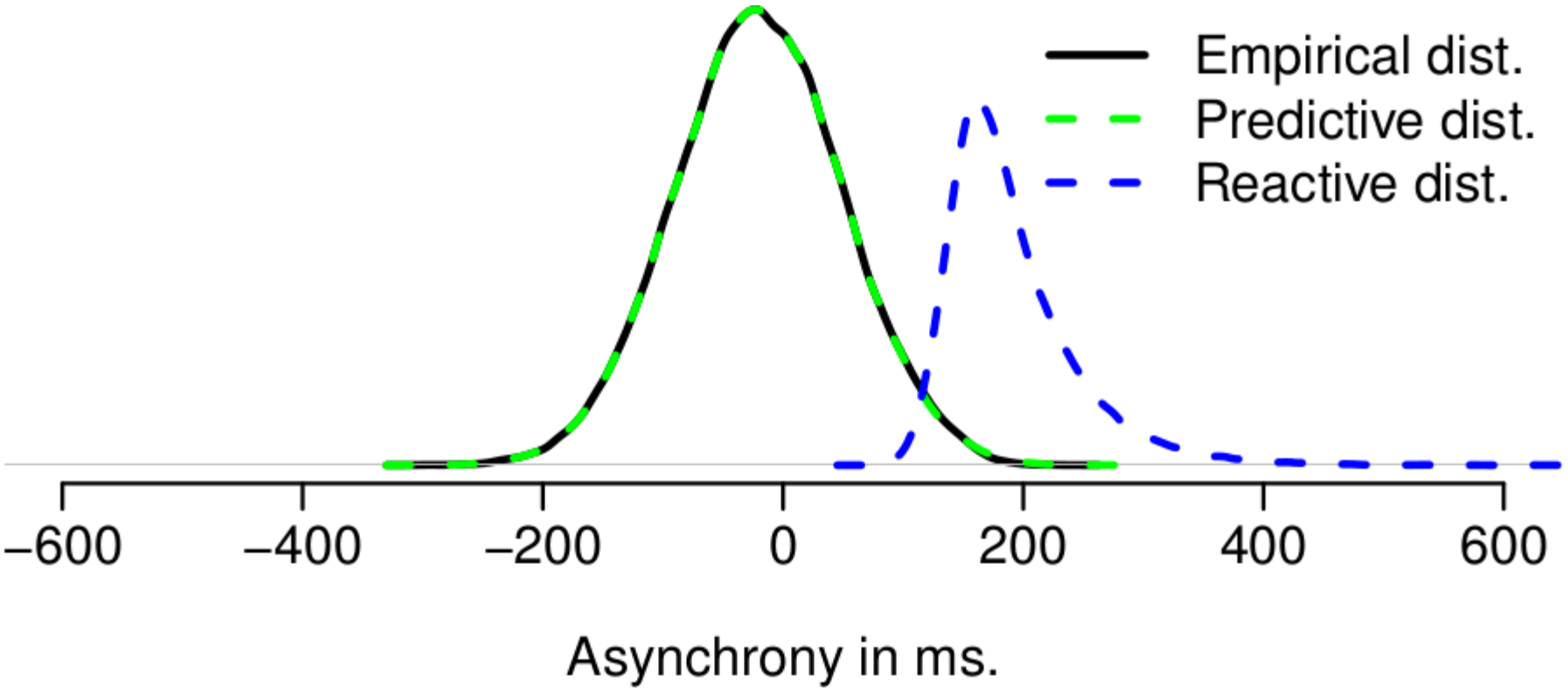
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
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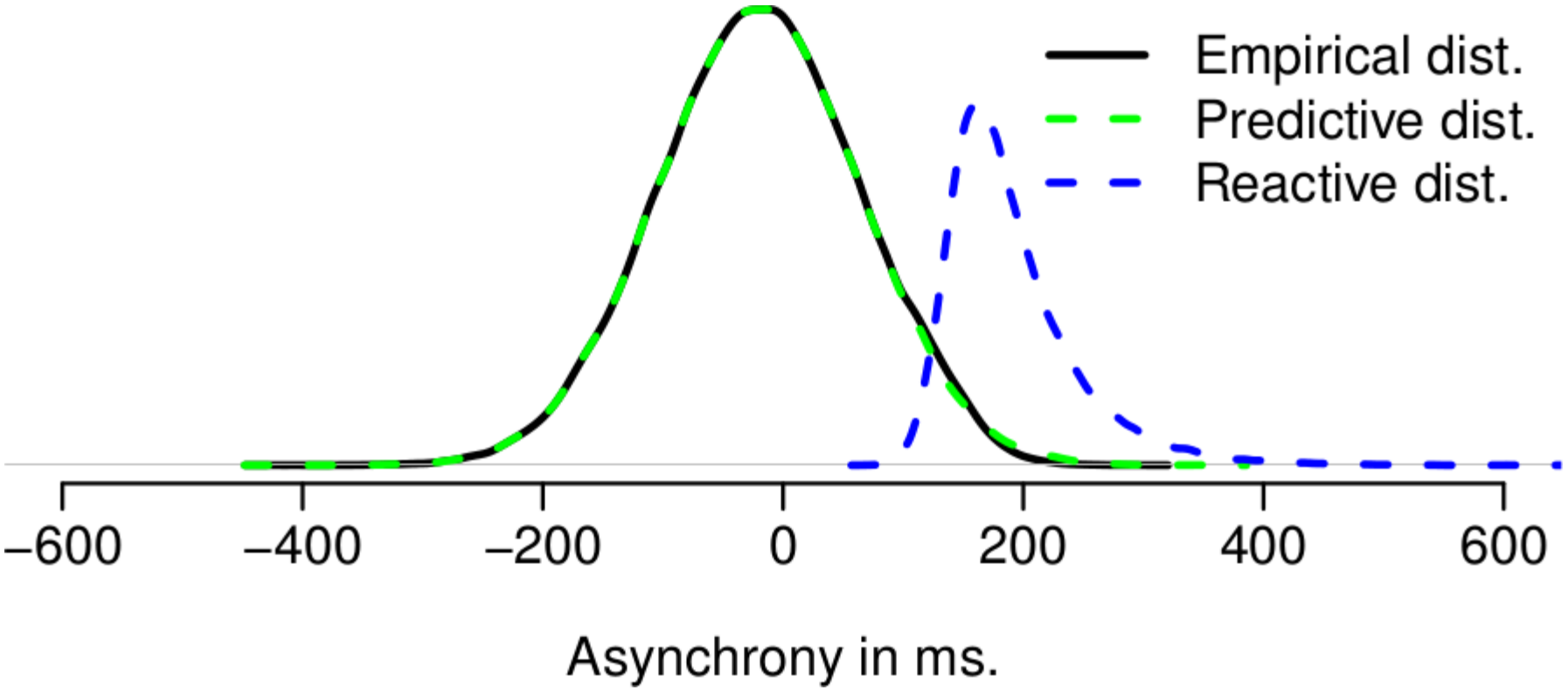
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
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−200
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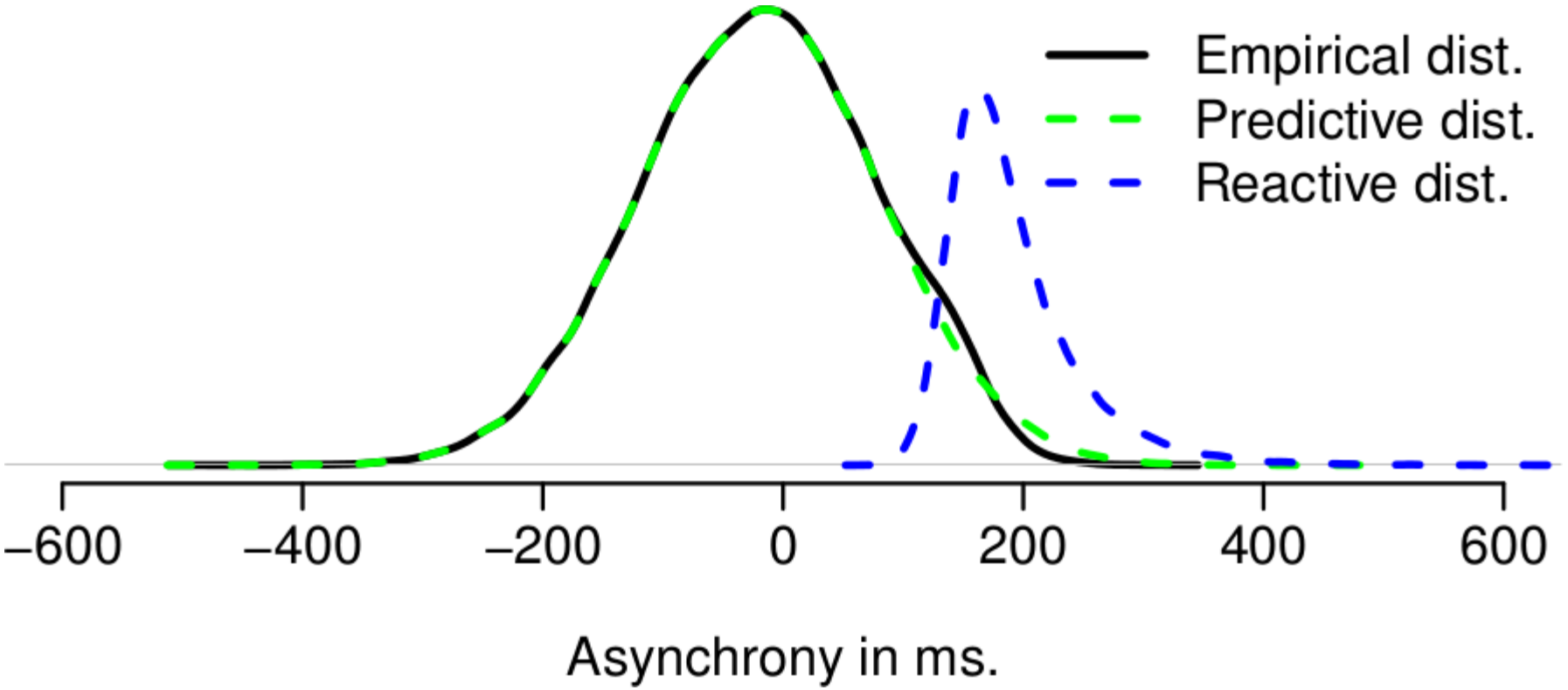
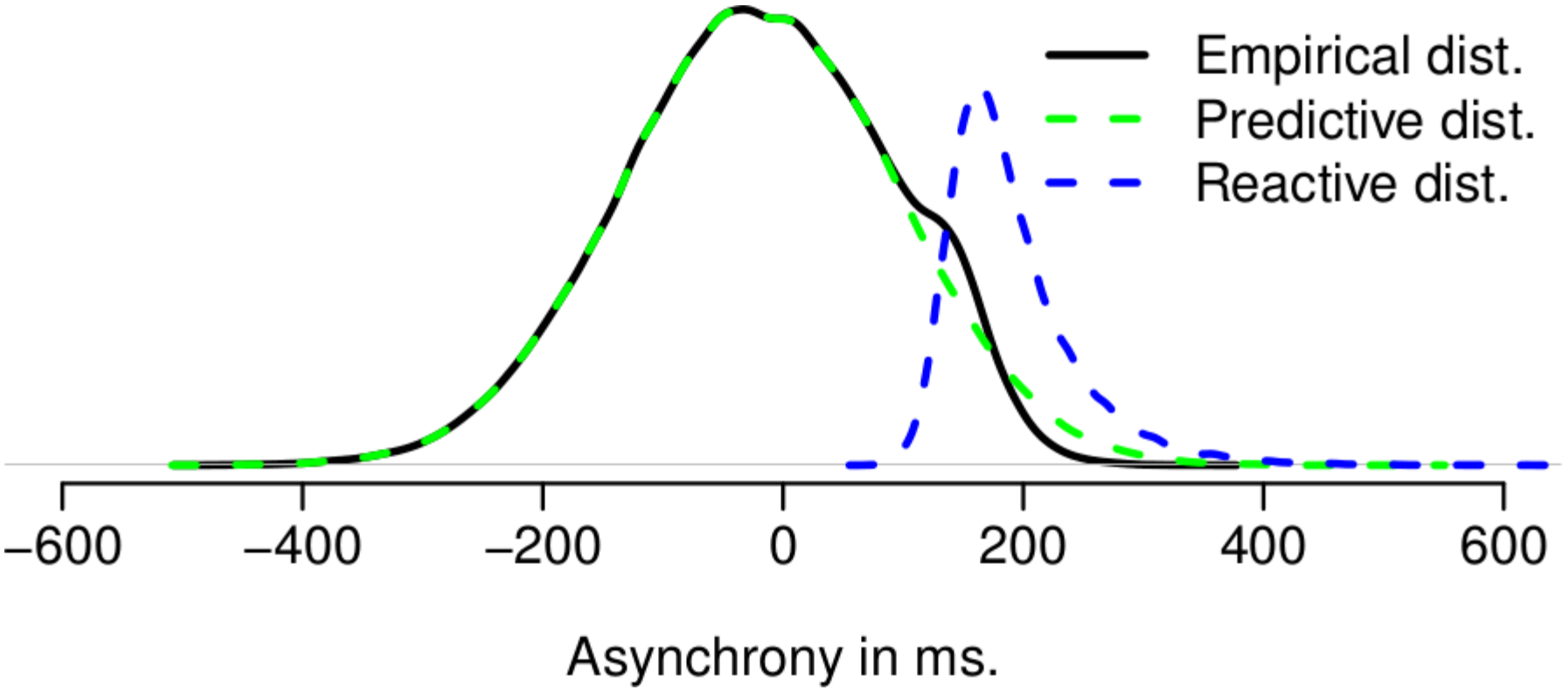
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
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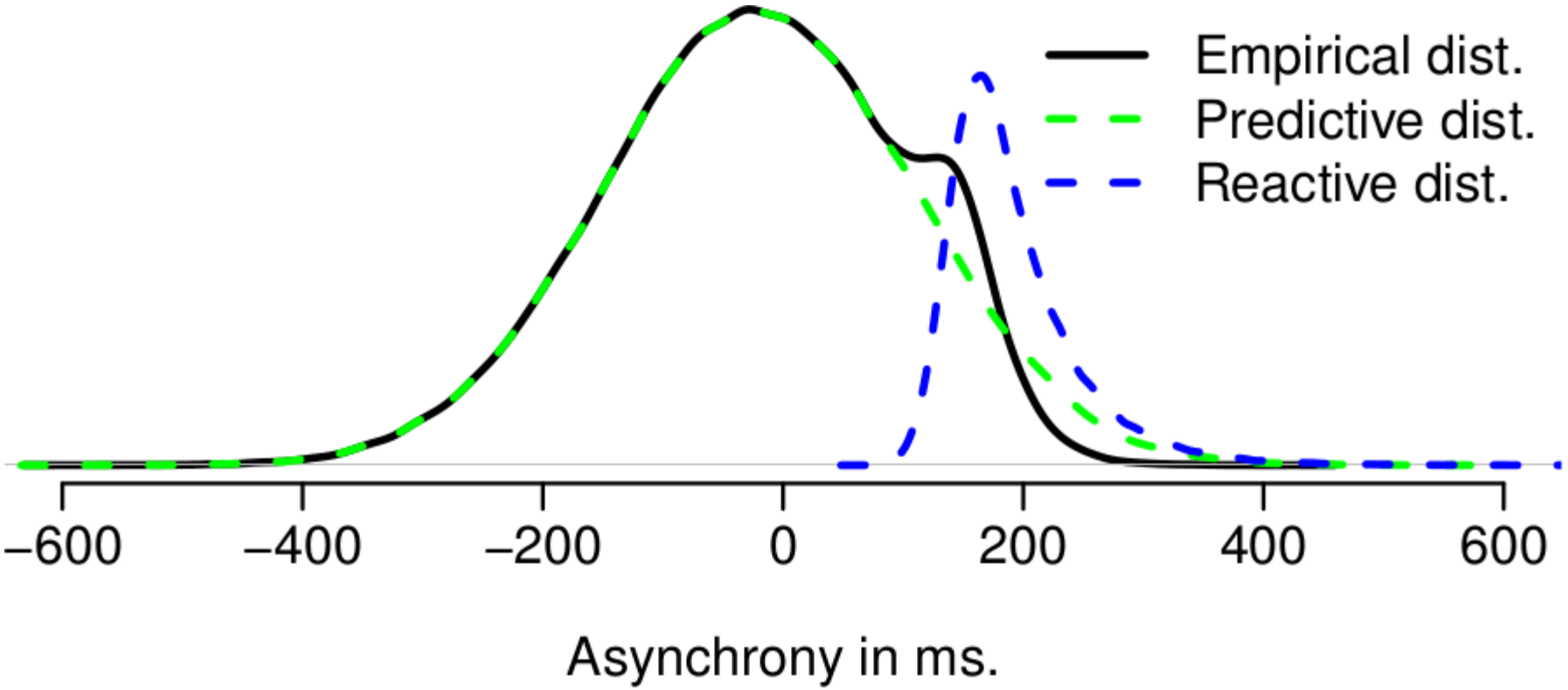
400
600
Asynchrony in ms.


Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
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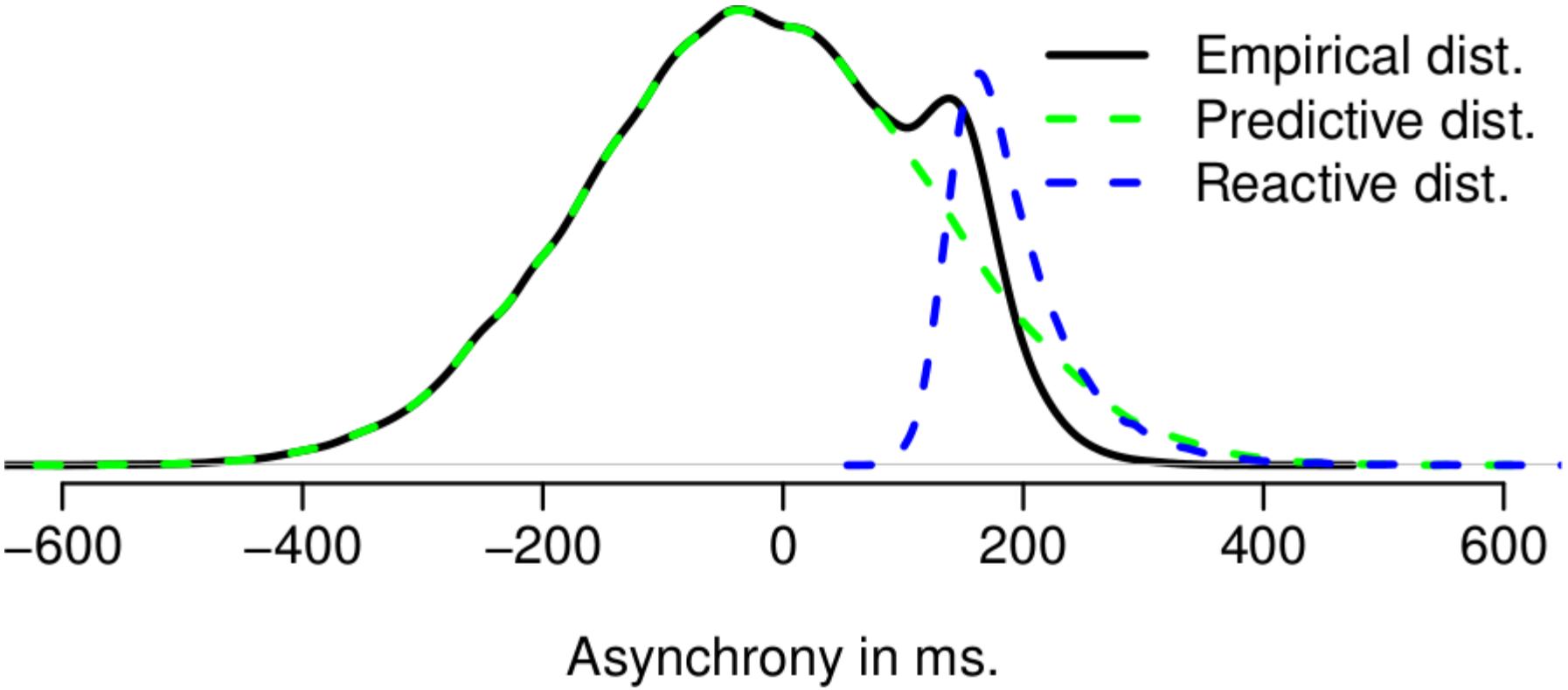
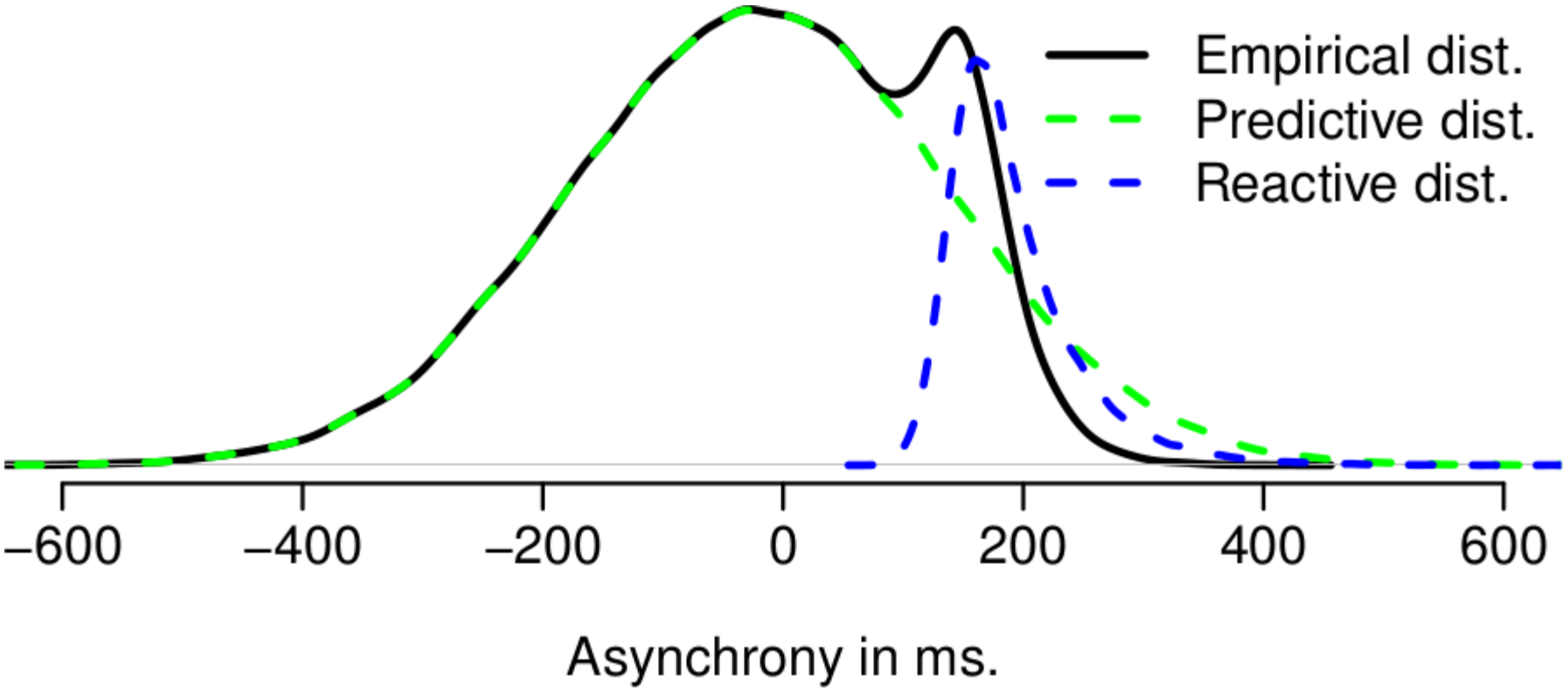
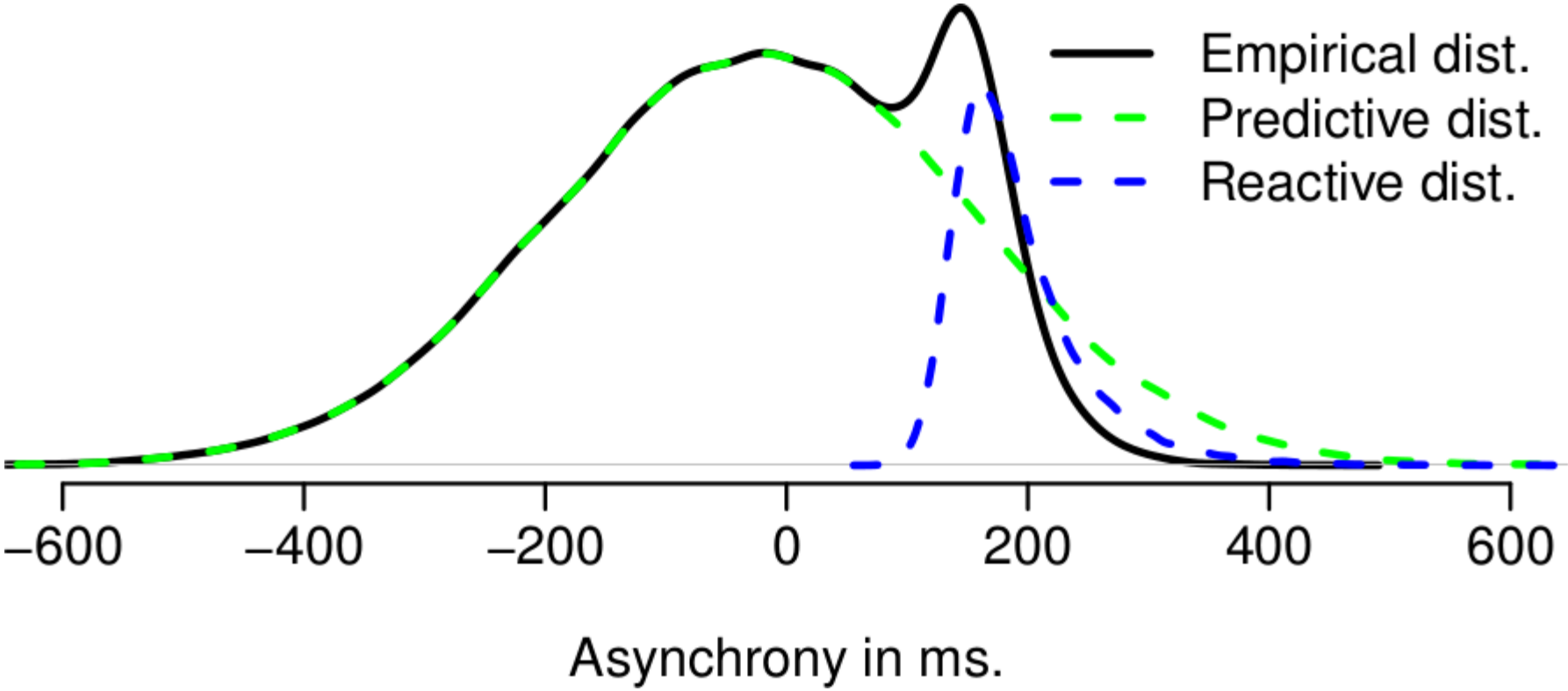
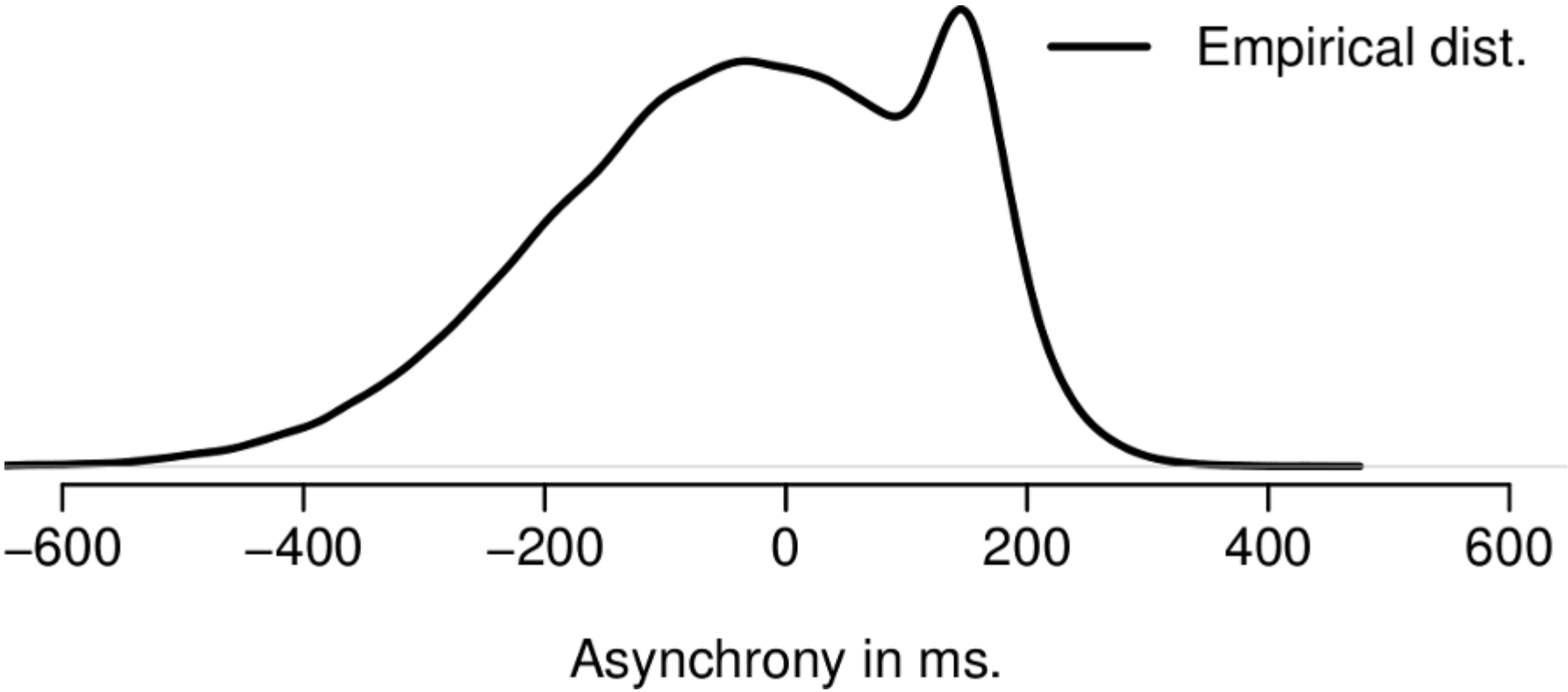
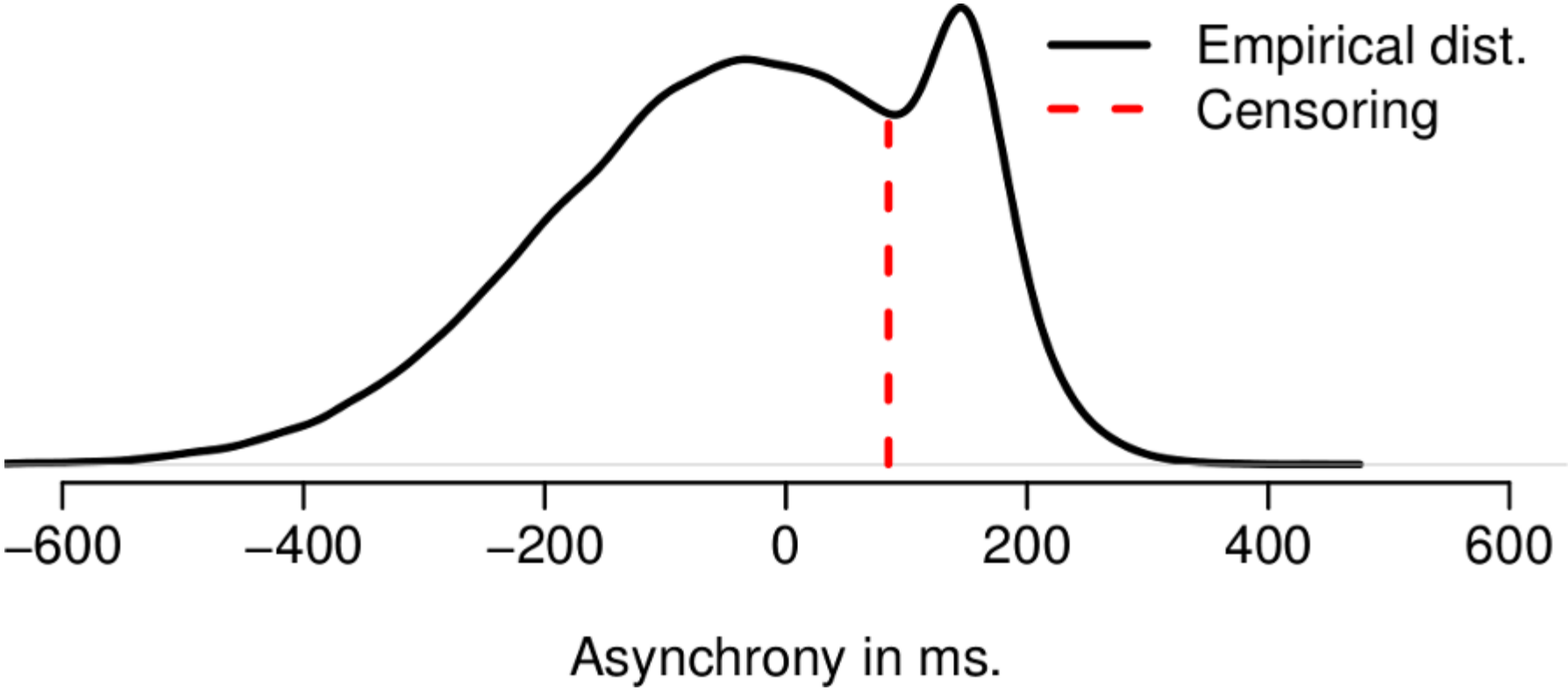
400
600
Asynchrony in ms.

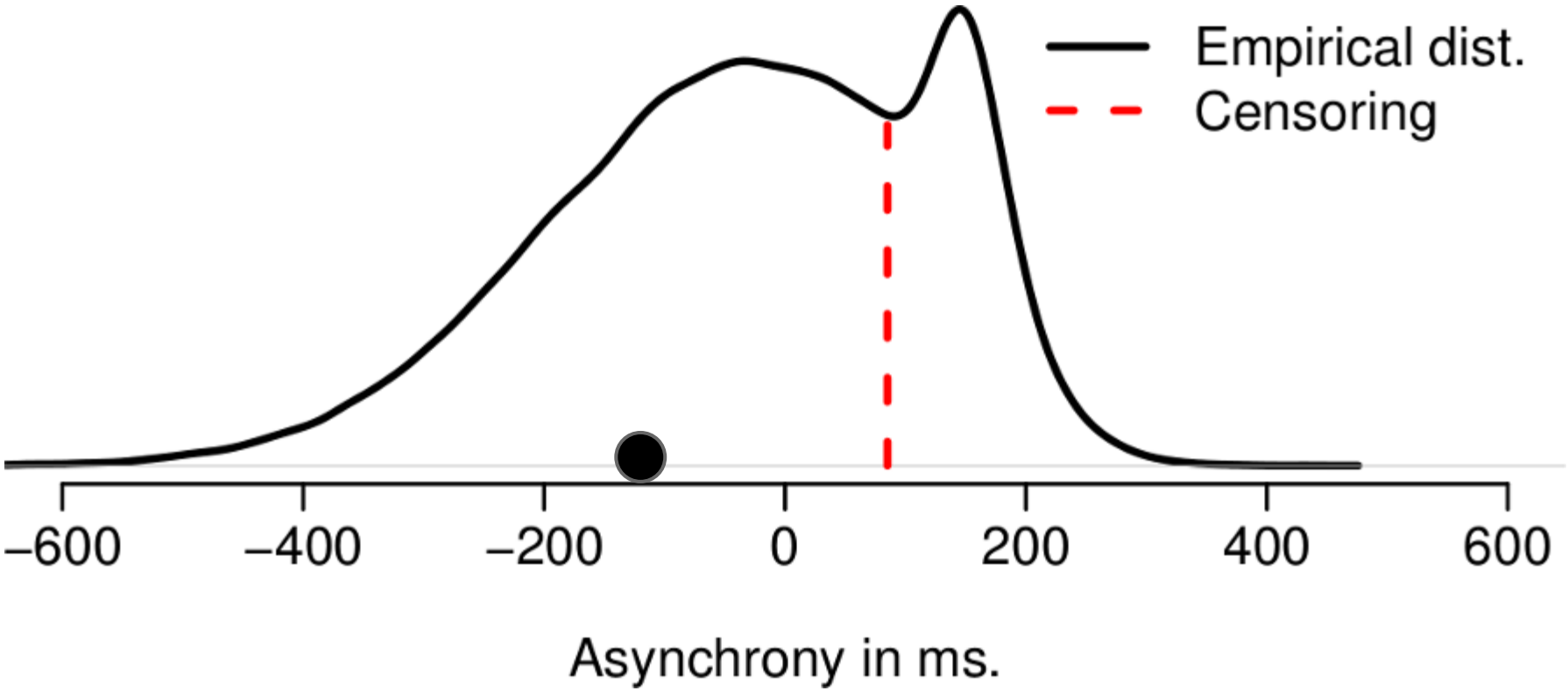

Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

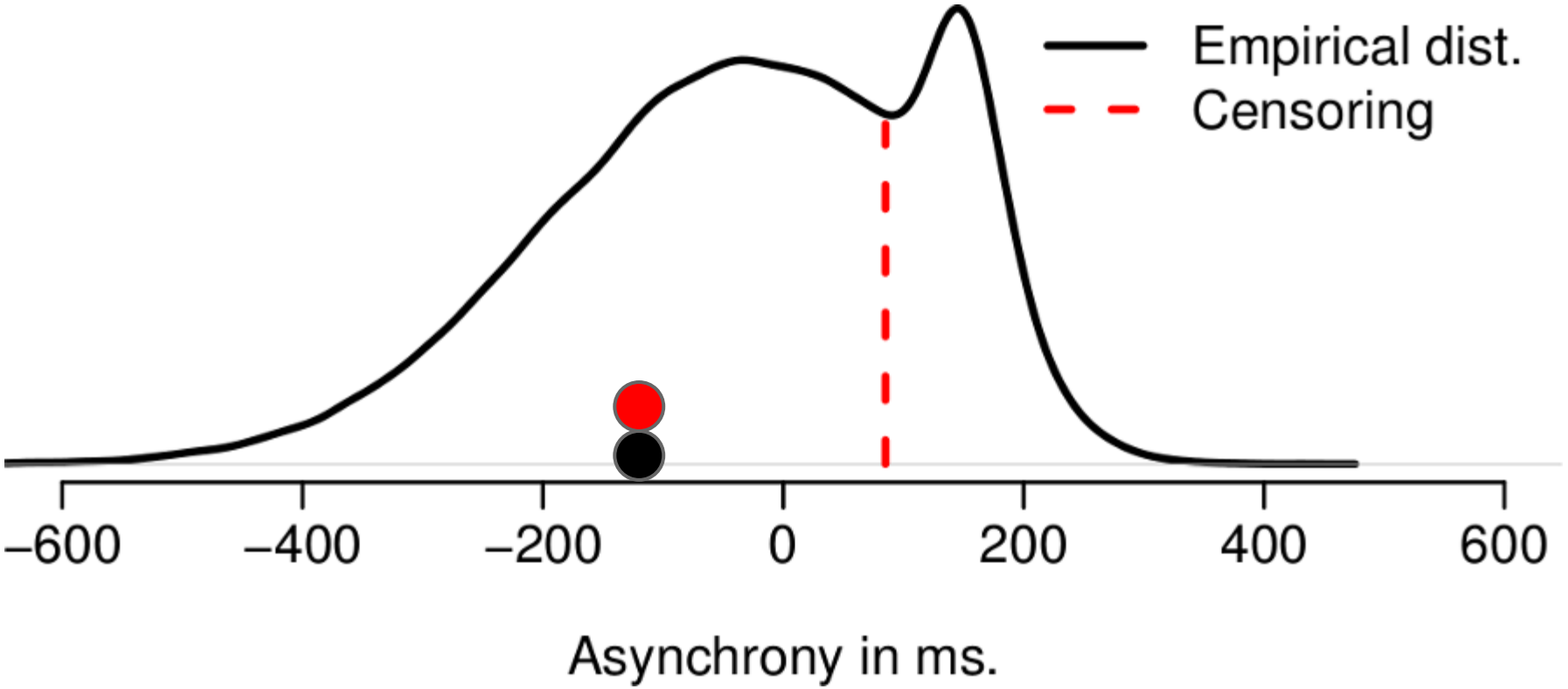

Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

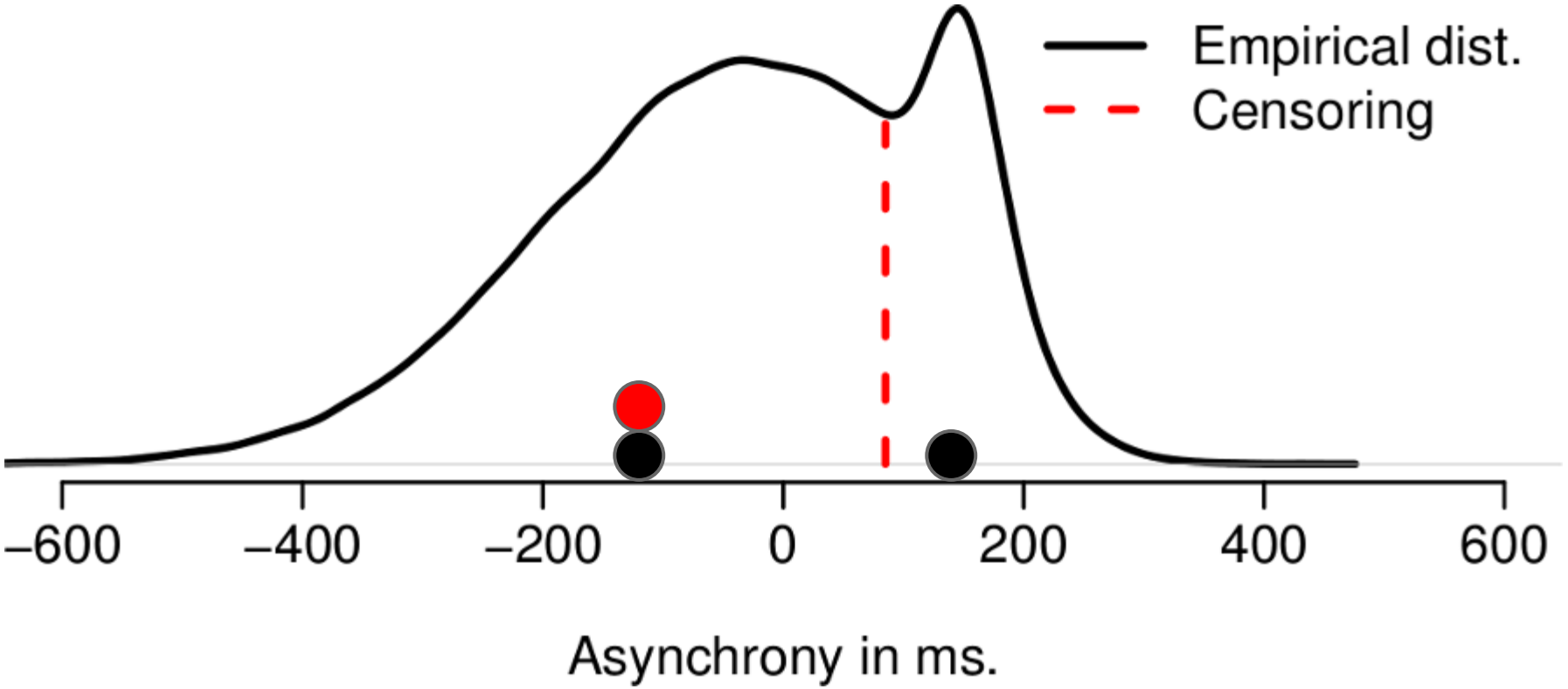

Empirical dist.
Predictive dist.
Reactive dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

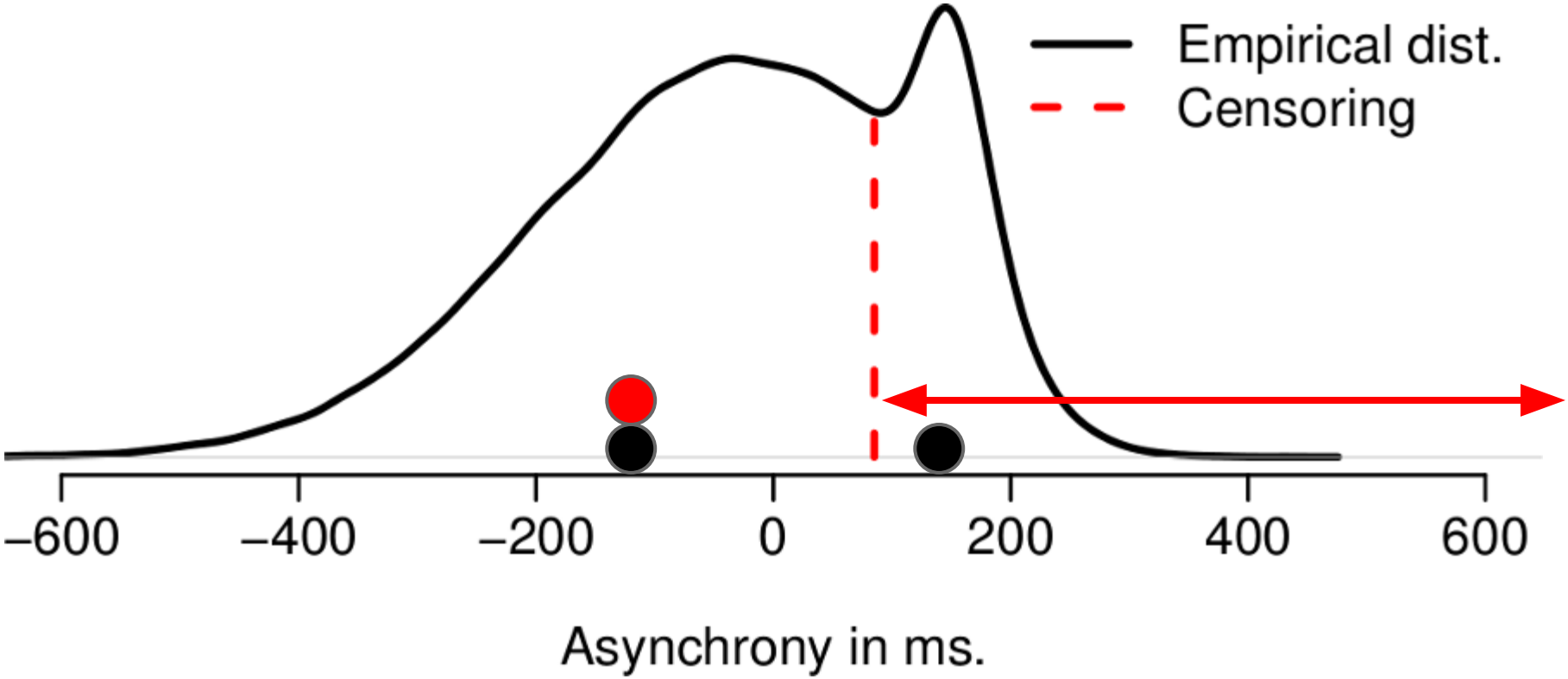

Empirical dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

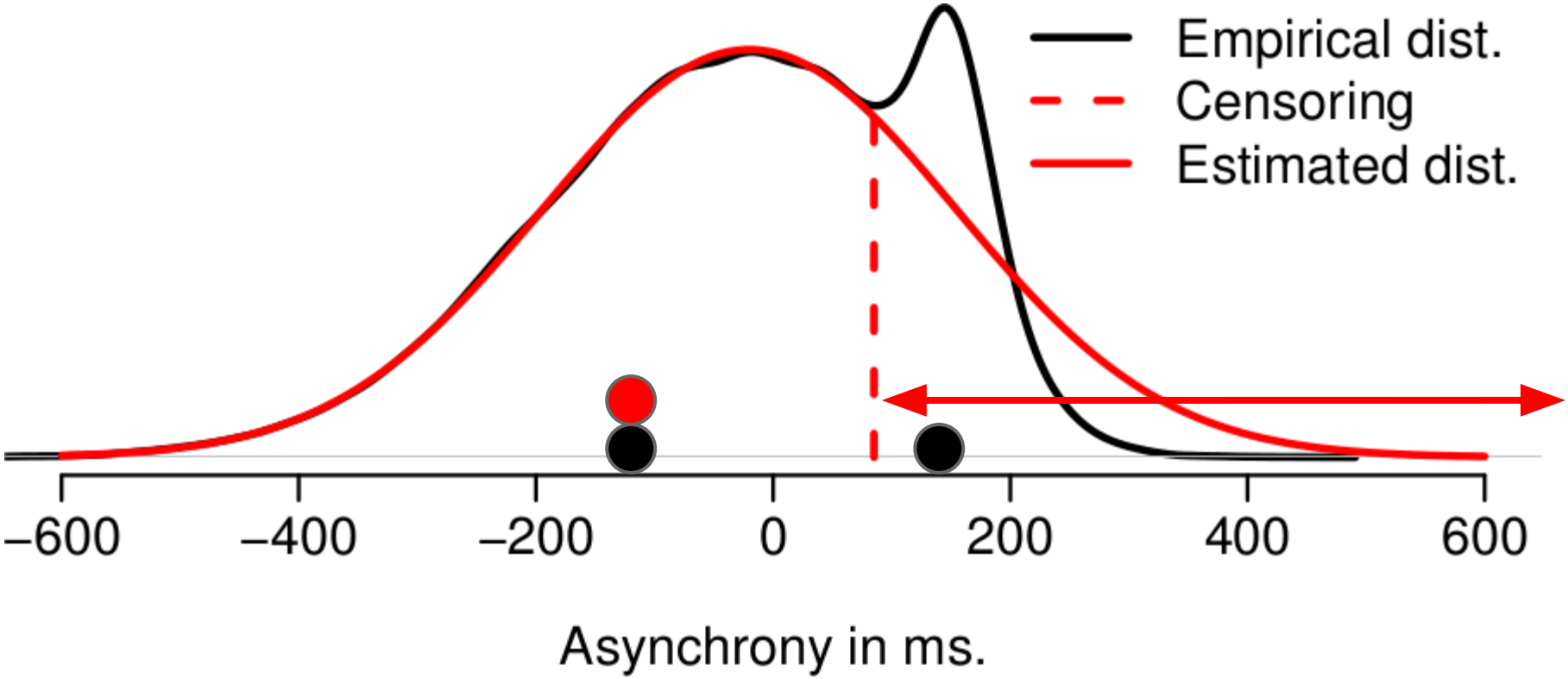

Empirical dist.
Censoring
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Censoring
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Censoring
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Censoring
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Censoring
−600
−400
−200
0
200
400
600
Asynchrony in ms.


Empirical dist.
Censoring
Estimated dist.
−600
−400
−200
0
200
400
600
Asynchrony in ms.

Estimating the Distribution of Asynchronies using Bayesian Statistics.

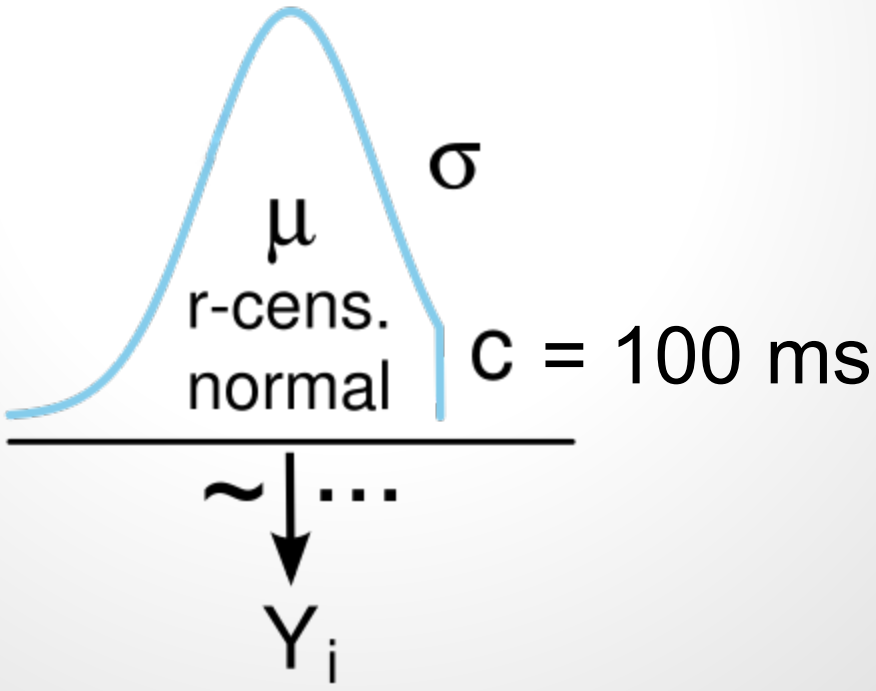
Advantages with Bayesian Statistics over Classical statistics.

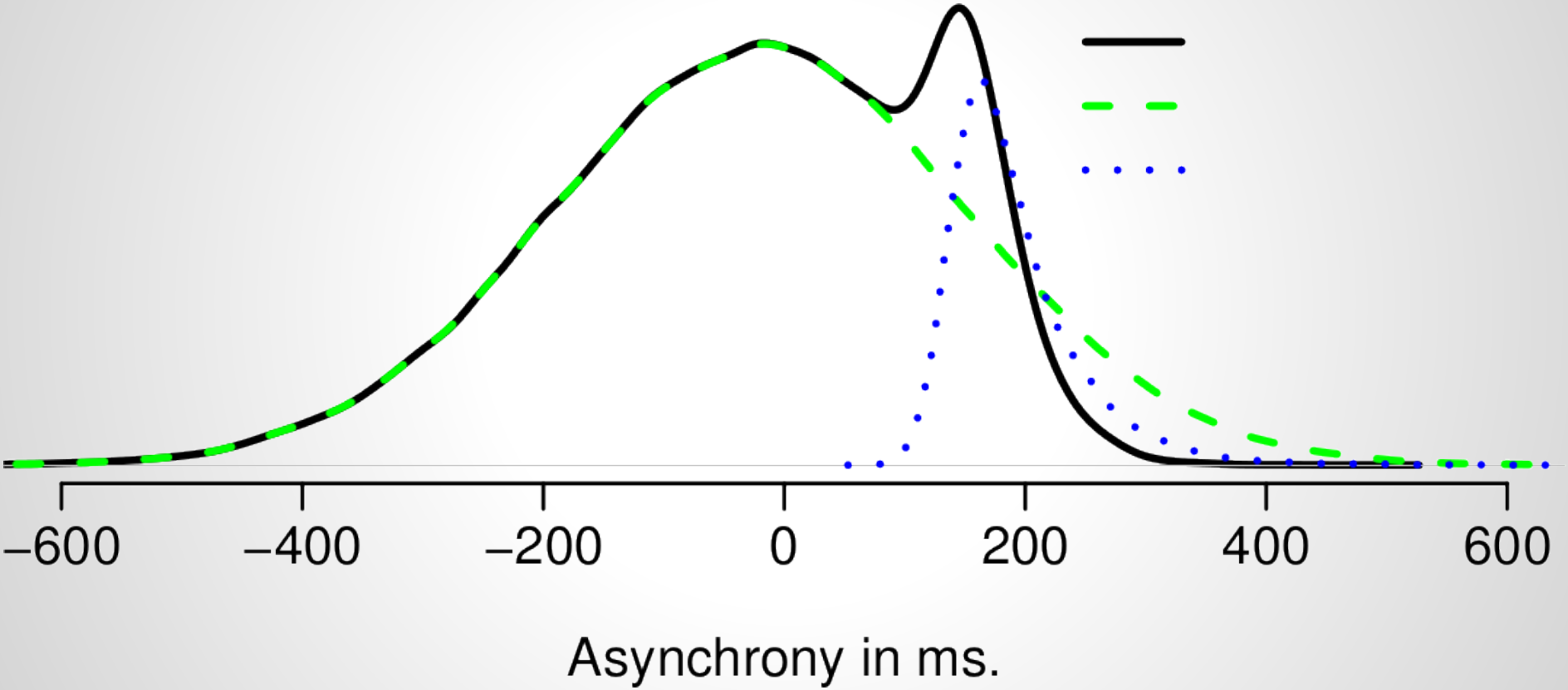
- It is simple and straightforward to implement the model I've proposed.
- It is also straightforward to extend the model to include hierarchical dependencies.
- It is possible (but not necessary) to include task related information in the analysis.

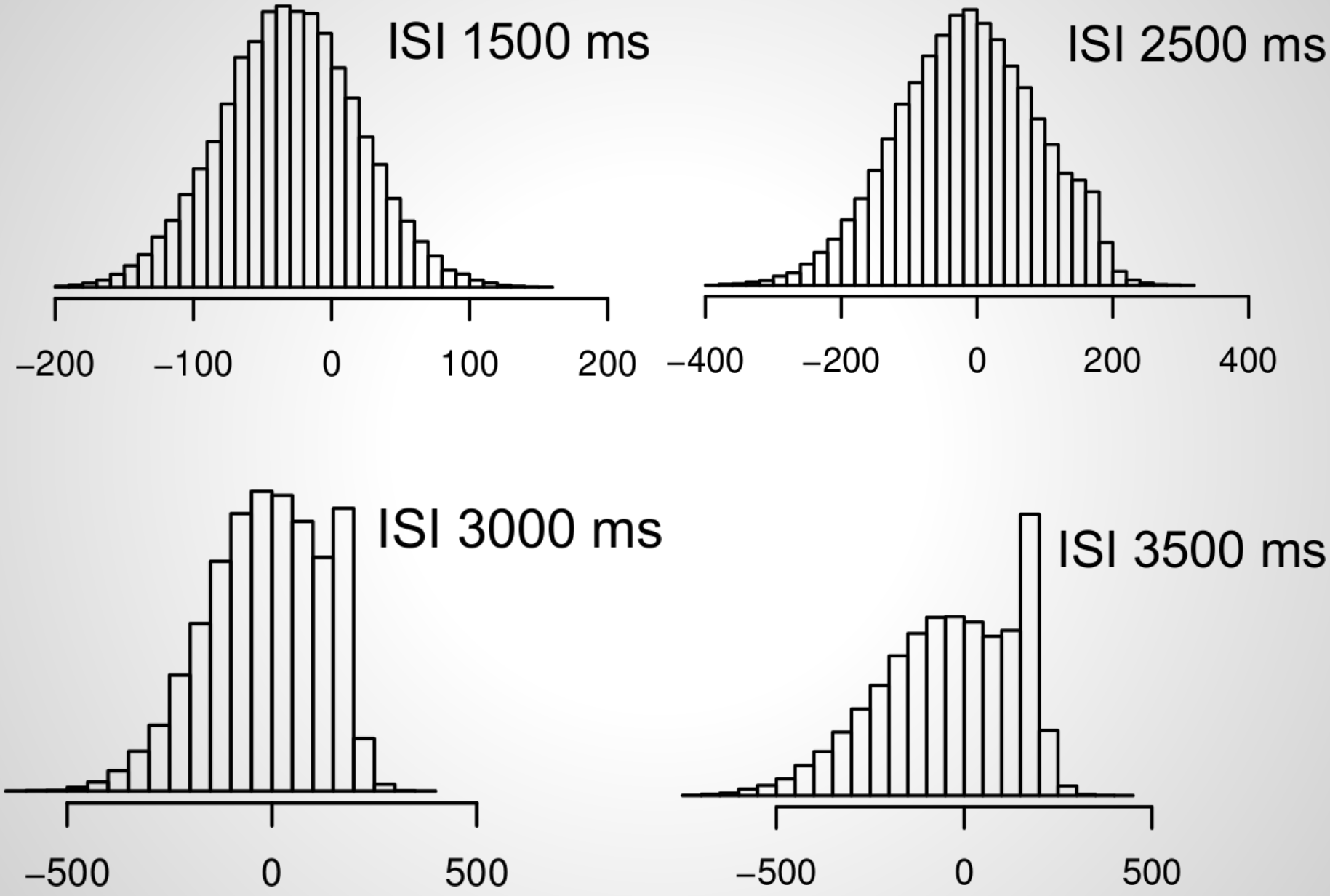
Advantages with Bayesian Statistics over Classical statistics.

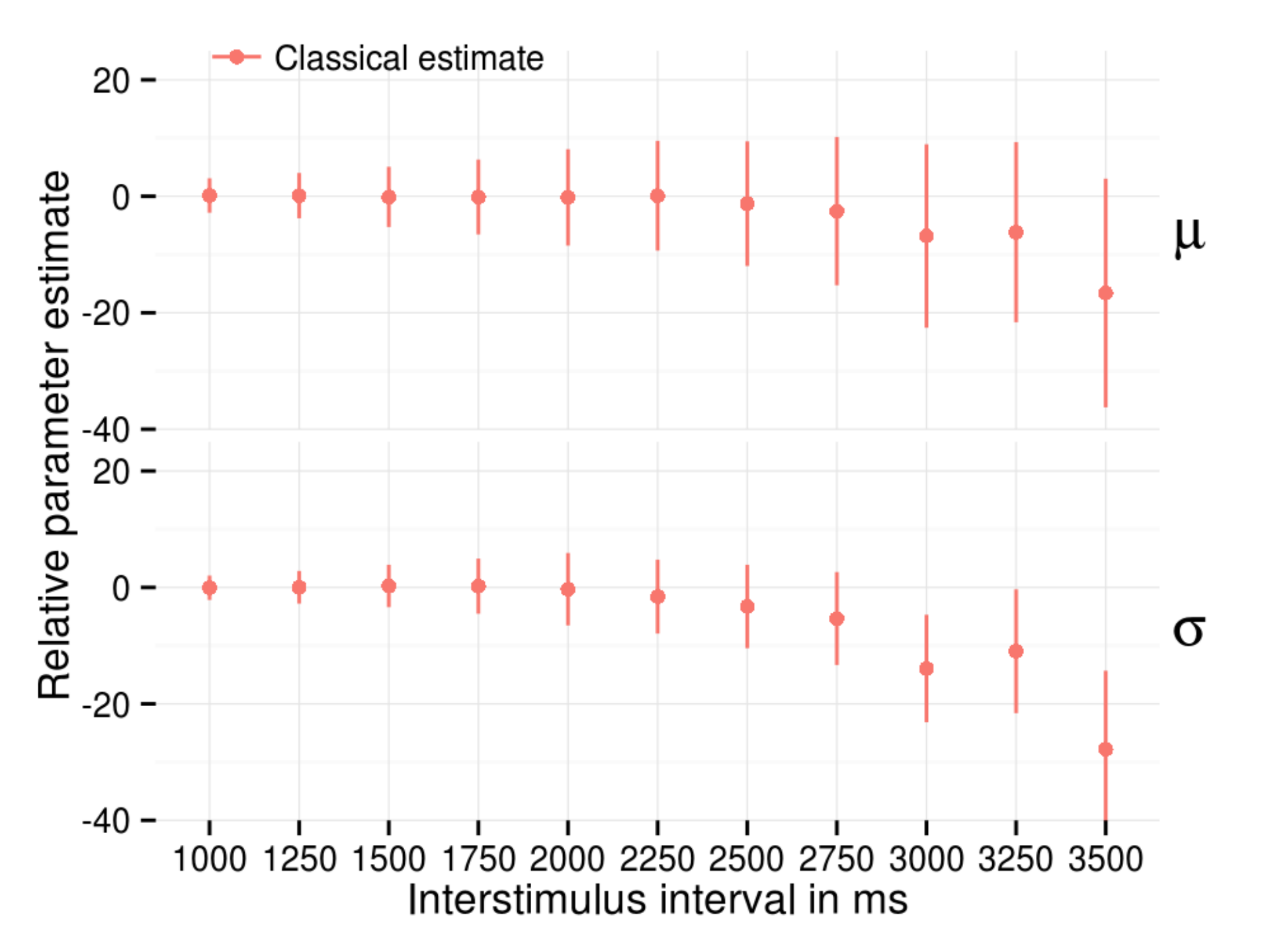
- More intuitive
  - Probabilities instead of p-values.
  - Can estimate support against **and for** a null hypothesis.
- Can also produce point values for use in classical ANOVAs.

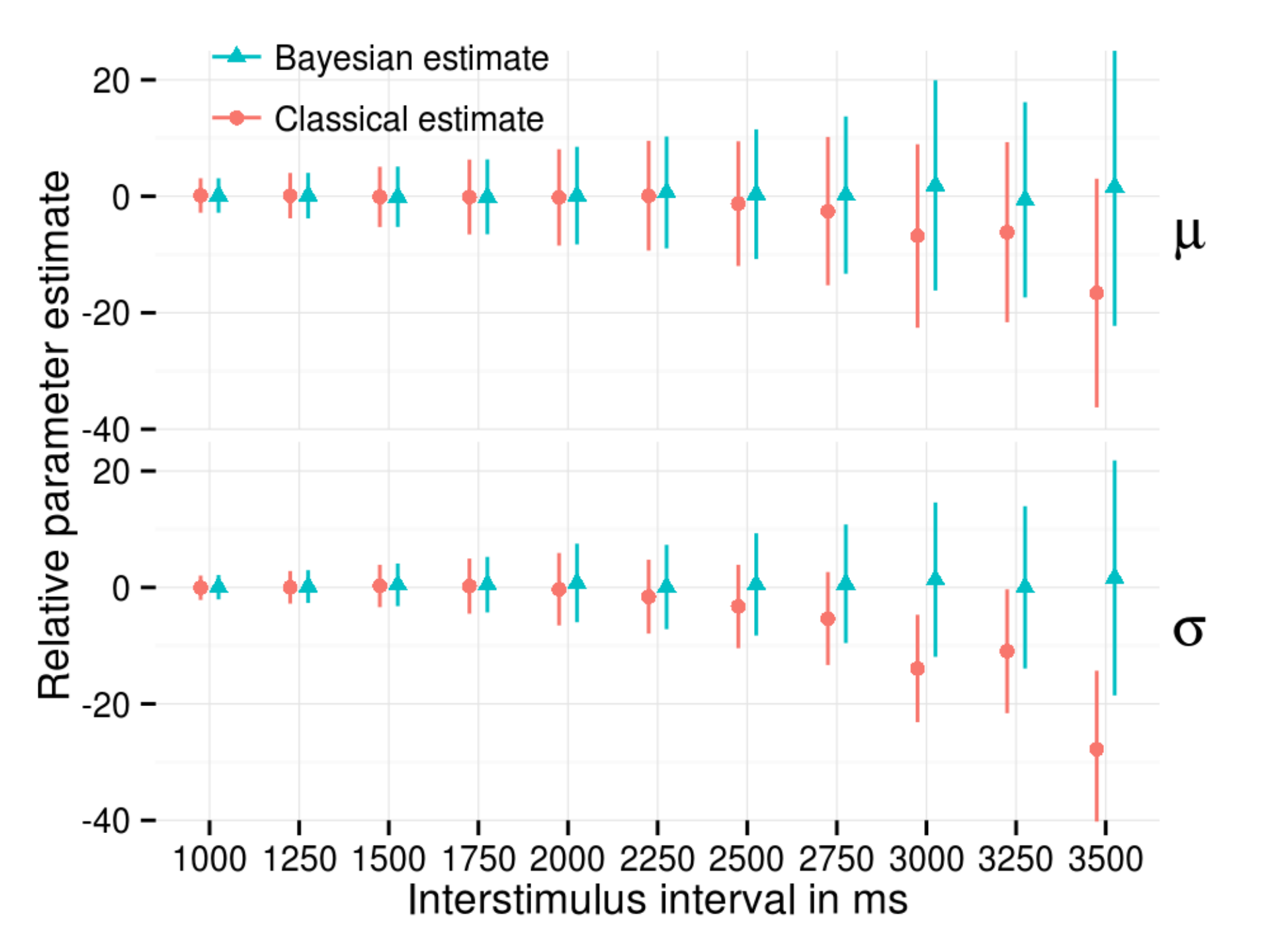
Single participant model




−600
−400
−200
0
200
400
600
Asynchrony in ms.


ISI 1500 ms
−200
−100
0
100
200
ISI 2500 ms
−400
−200
0
200
400
ISI 3000 ms
−500
0
500
ISI 3500 ms
−500
0
500


Classical estimate
20
0
-20
-40
μ
σ
Relative parameter estimate
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
3500
Interstimulus interval in ms


Bayesian estimate
Classical estimate
Relative parameter estimate
20
0
-20
-40
μ
σ
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
3500
Interstimulus interval in ms

Applied to data from Repp & Doggett (2007)

Tapping to a Very Slow Beat: A Comparison of Musicians and Nonmusicians

Bruno H. Repp
Haskins Laboratories

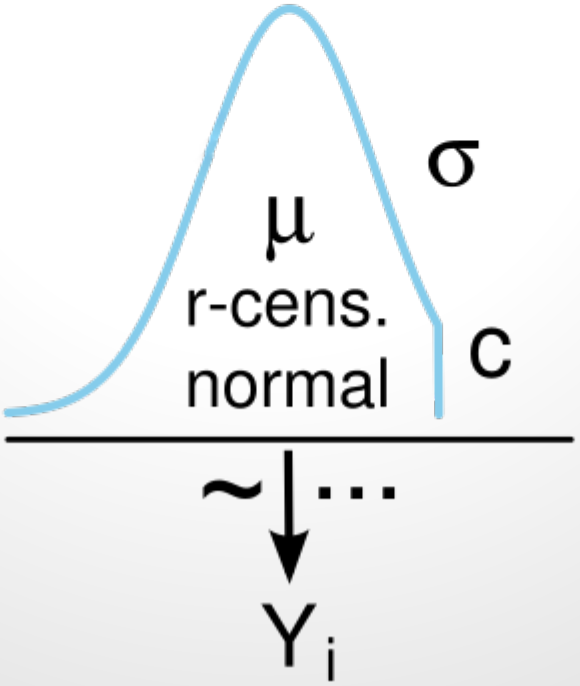
Rebecca Doggett
Yale University

When nonmusicians tap with isochronous auditory tone sequences, the taps typically precede the tone onsets. However, when the tone inter-onset interval (IOI) is increased beyond 2 s, an increasing proportion of taps follows the tone onsets by 150 ms or more. Such responses indicate reactions rather than anticipations, and they have been interpreted as reflecting a rate limit of synchronization related to a temporal limit of auditory working memory. In the present study, musicians

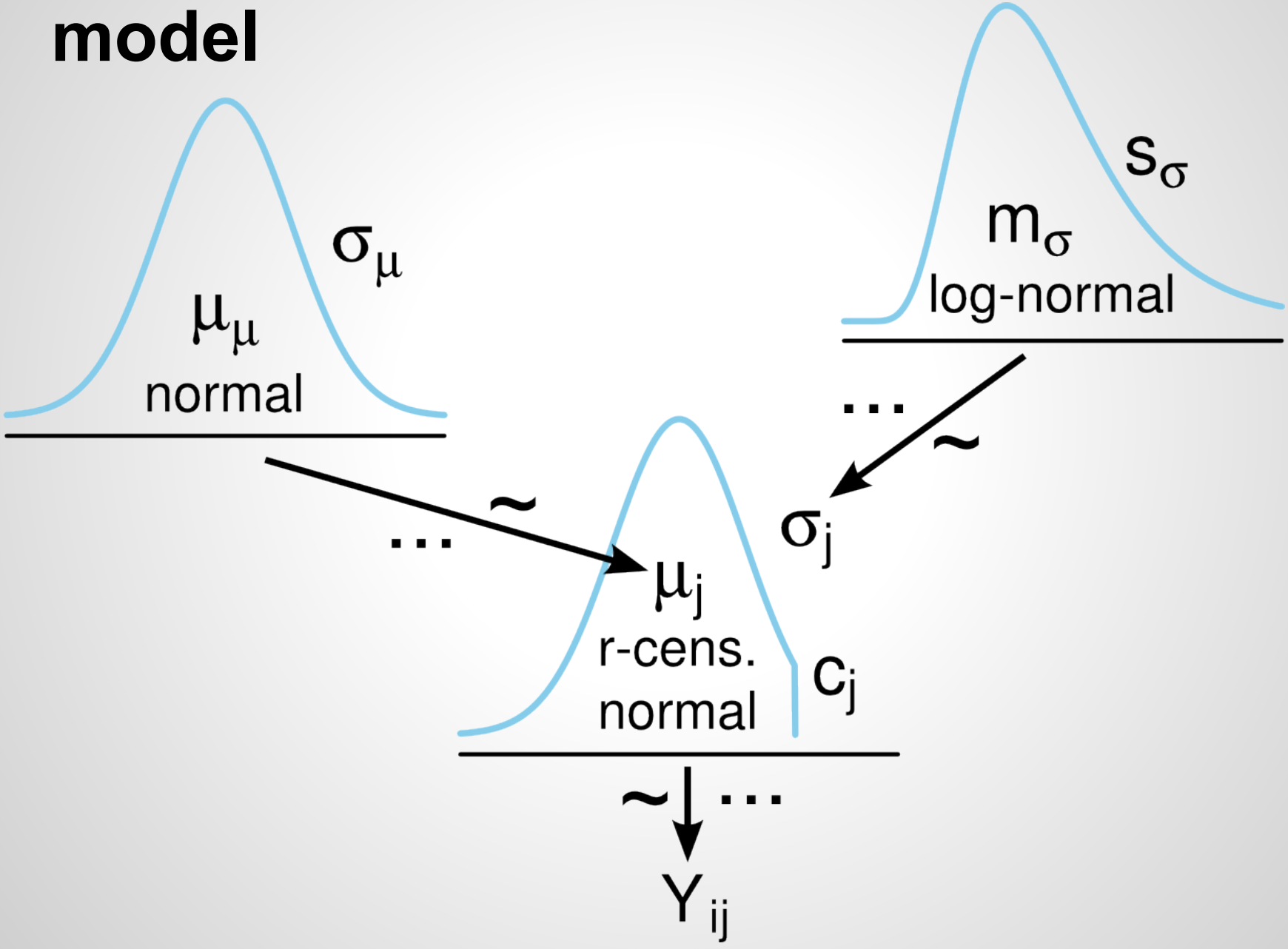
Rather, it probably reflects a temporal window of perceptual integration or attention within which tones are difficult to perceive as individual events. The upper rate limit for off-beat tapping, at IOIs of about 350 ms for musicians, is much lower (higher in terms of IOIs) than that for on-beat tapping. These rate limits or "synchronization thresholds" (Repp, 2003) are well defined by the occurrence of continuous phase drift, indicating an inability to synchronize, or, in the case of off-beat tapping, by a switch to on-beat tapping.

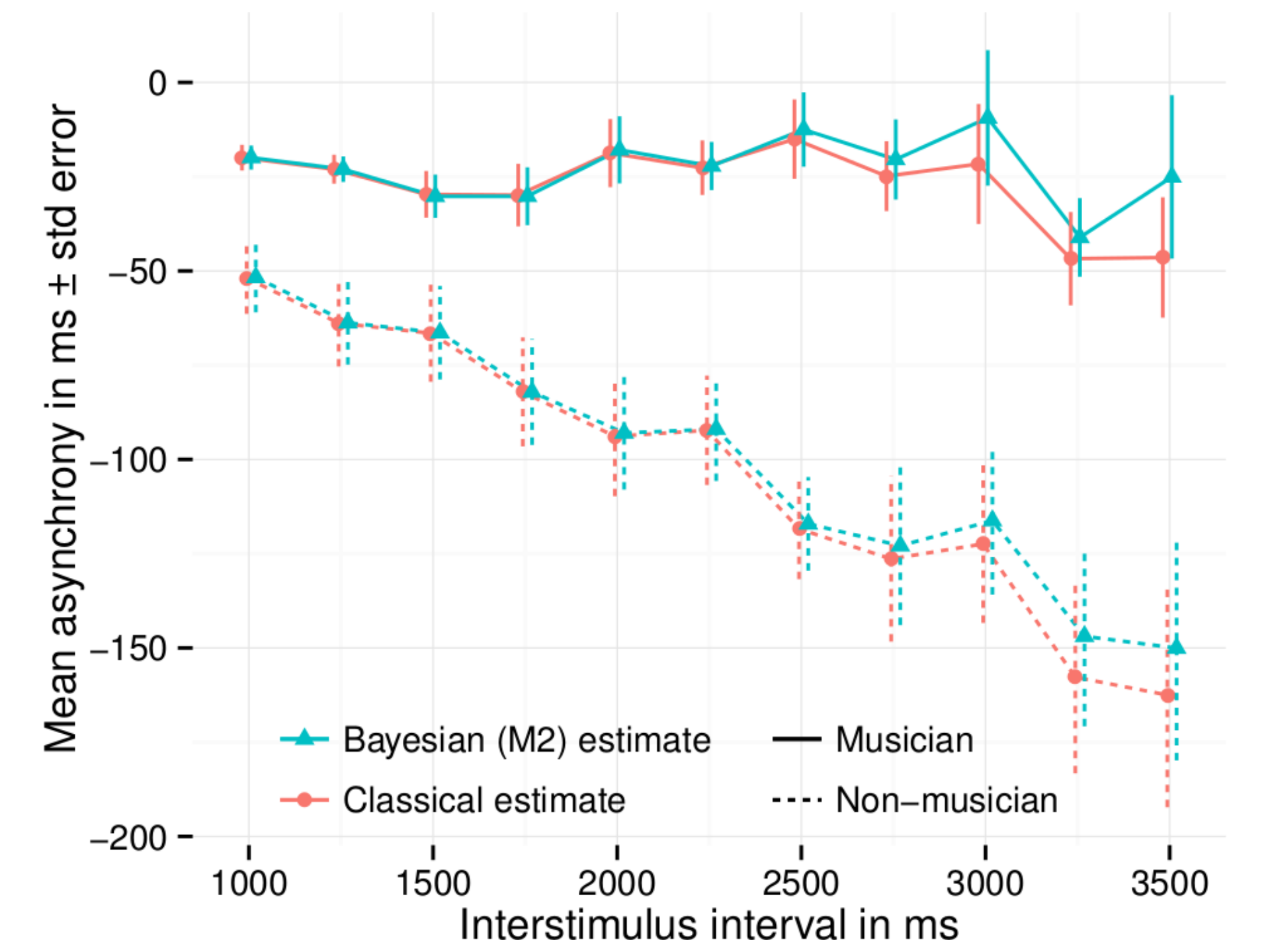
The present study is concerned with the question of whether there is also a lower rate limit of SMS, occurring at long IOIs. It has been noted repeatedly over the years that synchronization becomes subjectively difficult when the IOIs of a slow sequence are in the vicinity

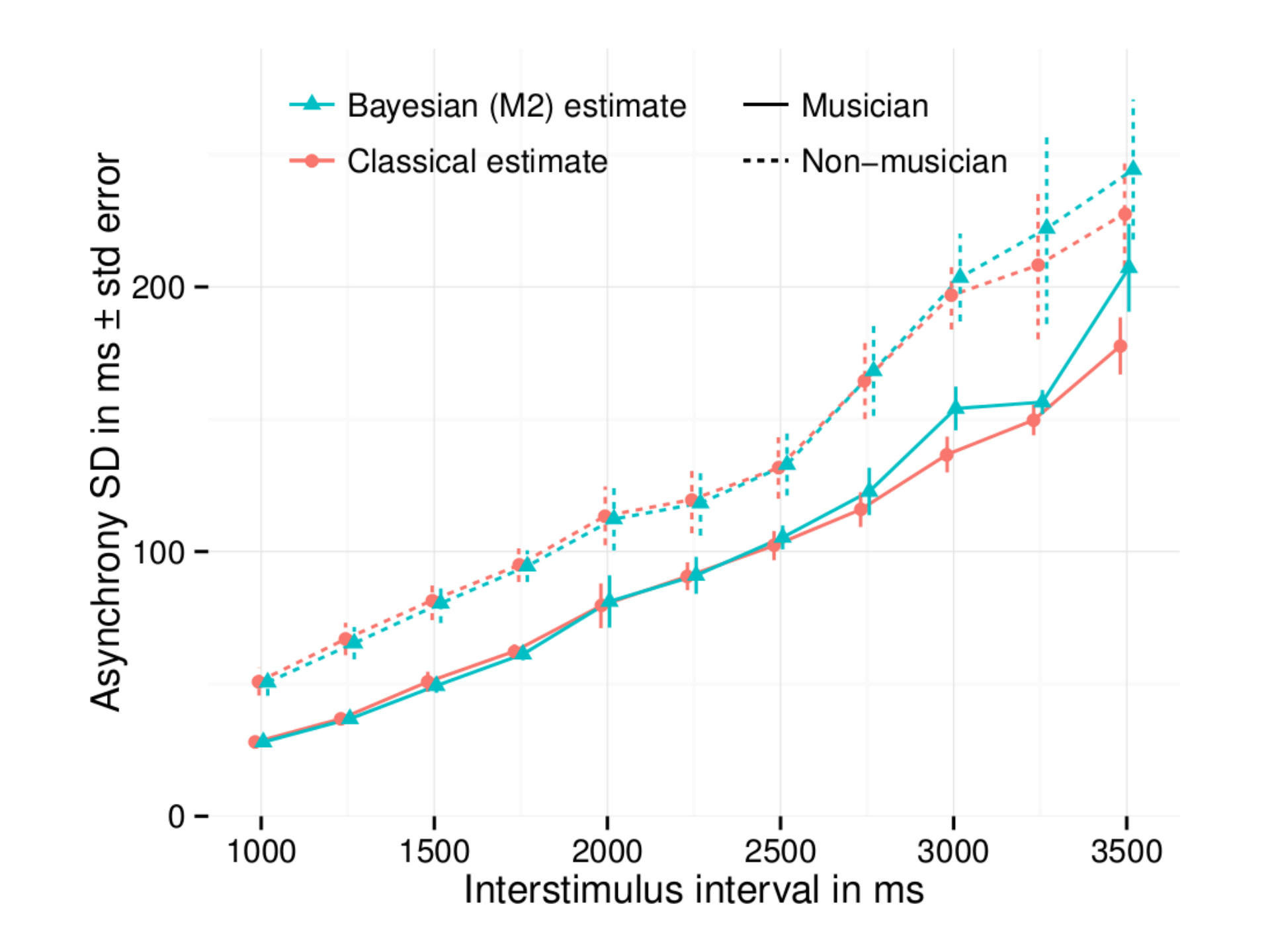
Single participant model



Multiple (hierarchical) participant model




0
−50
−100
−150
−200
Mean asynchrony in ms ± std error
1000
1500
2000
2500
3000
3500
Interstimulus interval in ms
Bayesian (M2) estimate
Classical estimate
Musician
Non−musician


Bayesian (M2) estimate
Classical estimate
Musician
Non−musician
Asynchrony SD in ms ± std error
0
100
200
1000
1500
2000
2500
3000
3500
Interstimulus interval in ms

Possible Extensions

- Interresponse intervals.

Possible Extensions

- Interresponse intervals.
- Estimation of time series models:
  - Variance component models.
  - Error correction models.

In Conclusion

- Asynchronies are not normally distributed at slow tempi (interstimulus interval > 2000 ms).

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In Conclusion

- Asynchronies are not normally distributed at slow tempi (interstimulus interval > 2000 ms).
- I've presented a model of why this happens.
- I've implemented a Bayesian model that accurately estimates the distribution of predictive asynchronies at both slow and fast tempi.

If You Want to Use the Model...

- Mail me: rasmus.baath@lucs.lu.se

If You Want to Use the Model...

- Mail me: rasmus.baath@lucs.lu.se
- Check my web page: www.sumsar.net

If You Want to Use the Model...

- Mail me: rasmus.baath@lucs.lu.se
- Check my web page: www.sumsar.net
- Talk to me!

References

- Chen, Y., Ding, M., & Kelso, J. (1997). Long Memory Processes (1/fα Type) in Human Coordination. *Physical Review Letters*, 79(22), 4501–4504.
- Mates, J., Müller, U., Radil, T., & Pöppel, E. (1994). Temporal Integration in Sensorimotor Synchronization. *Journal of Cognitive Neuroscience*, 6(4), 332–340.
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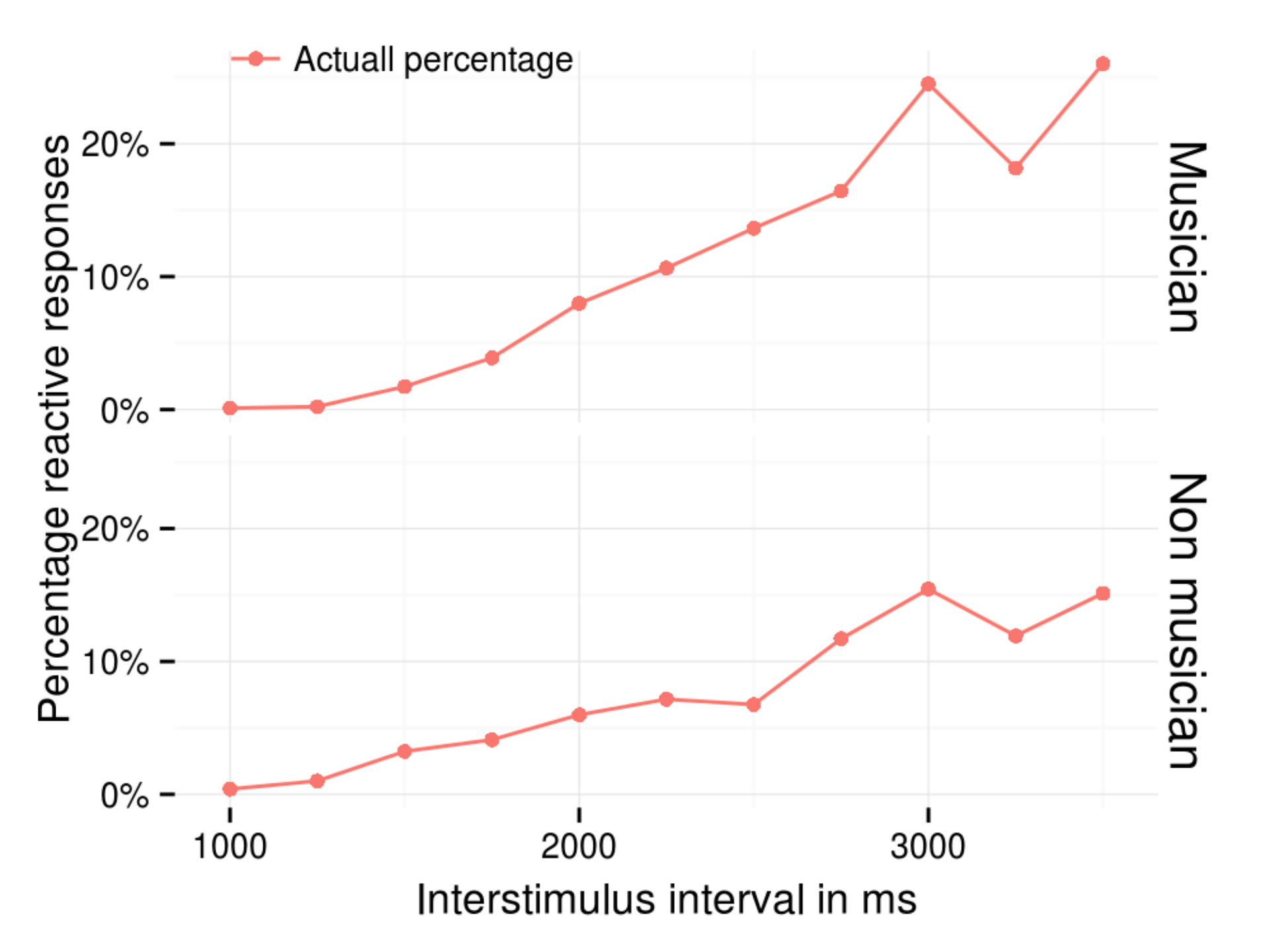
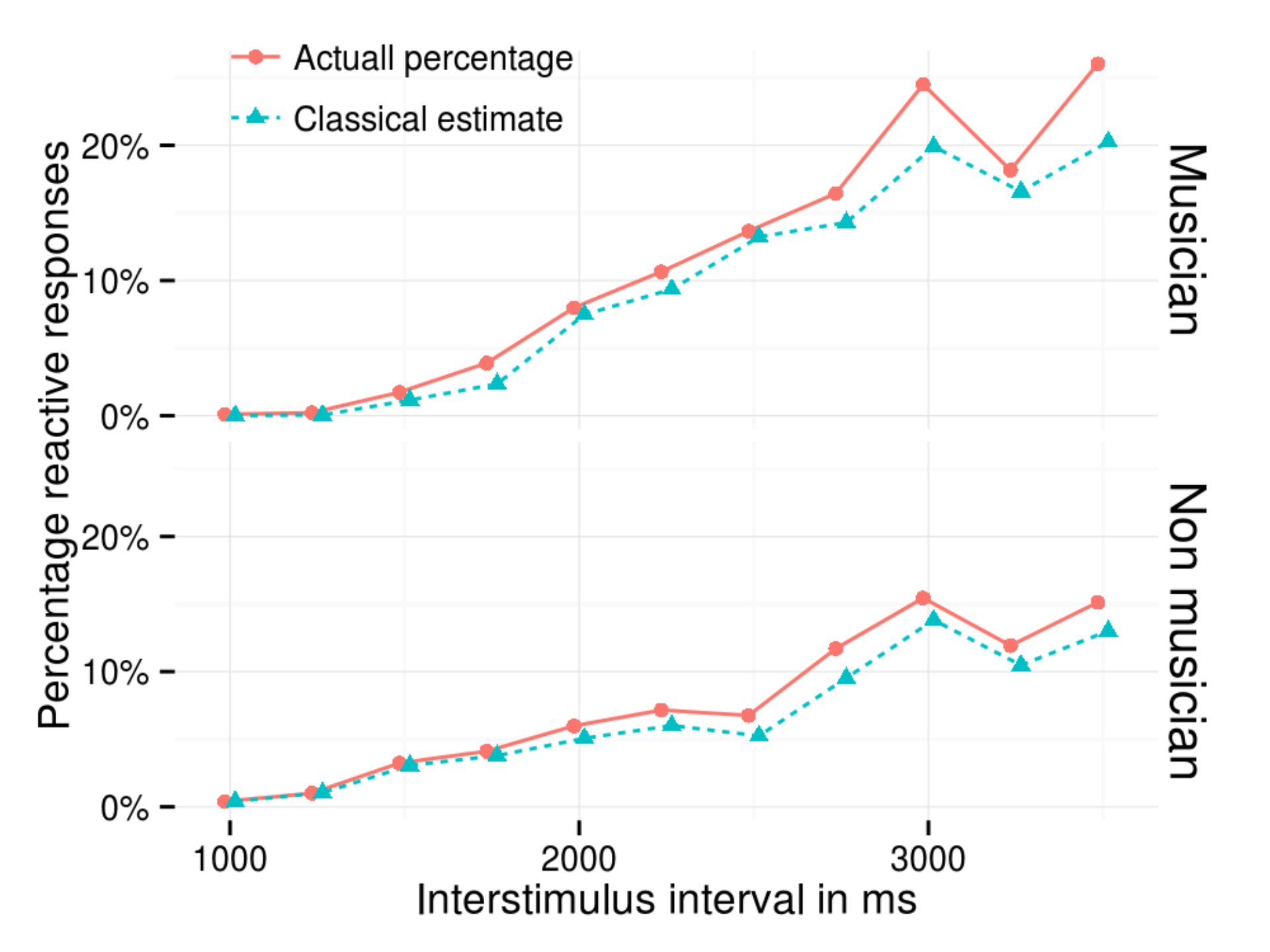
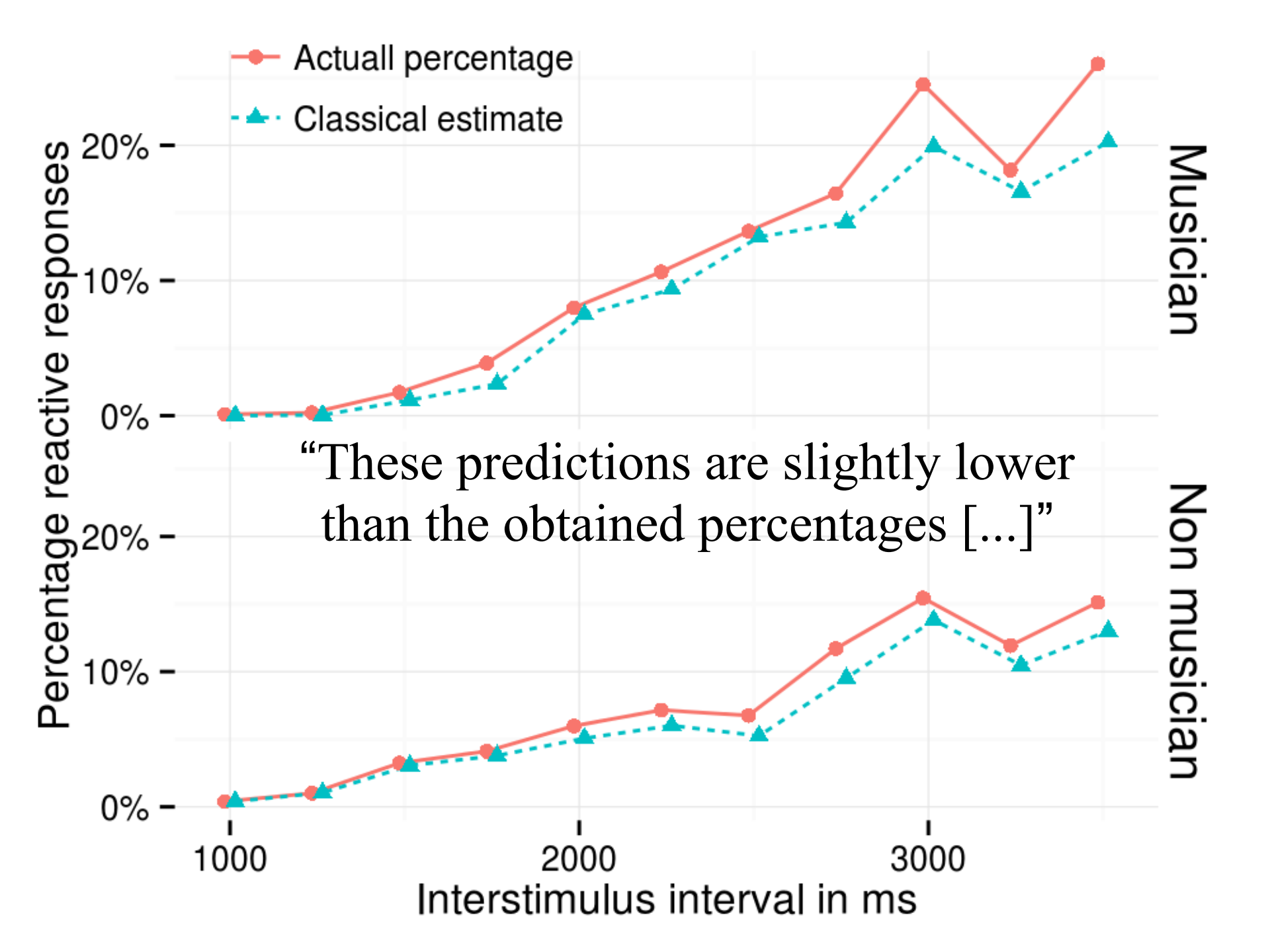
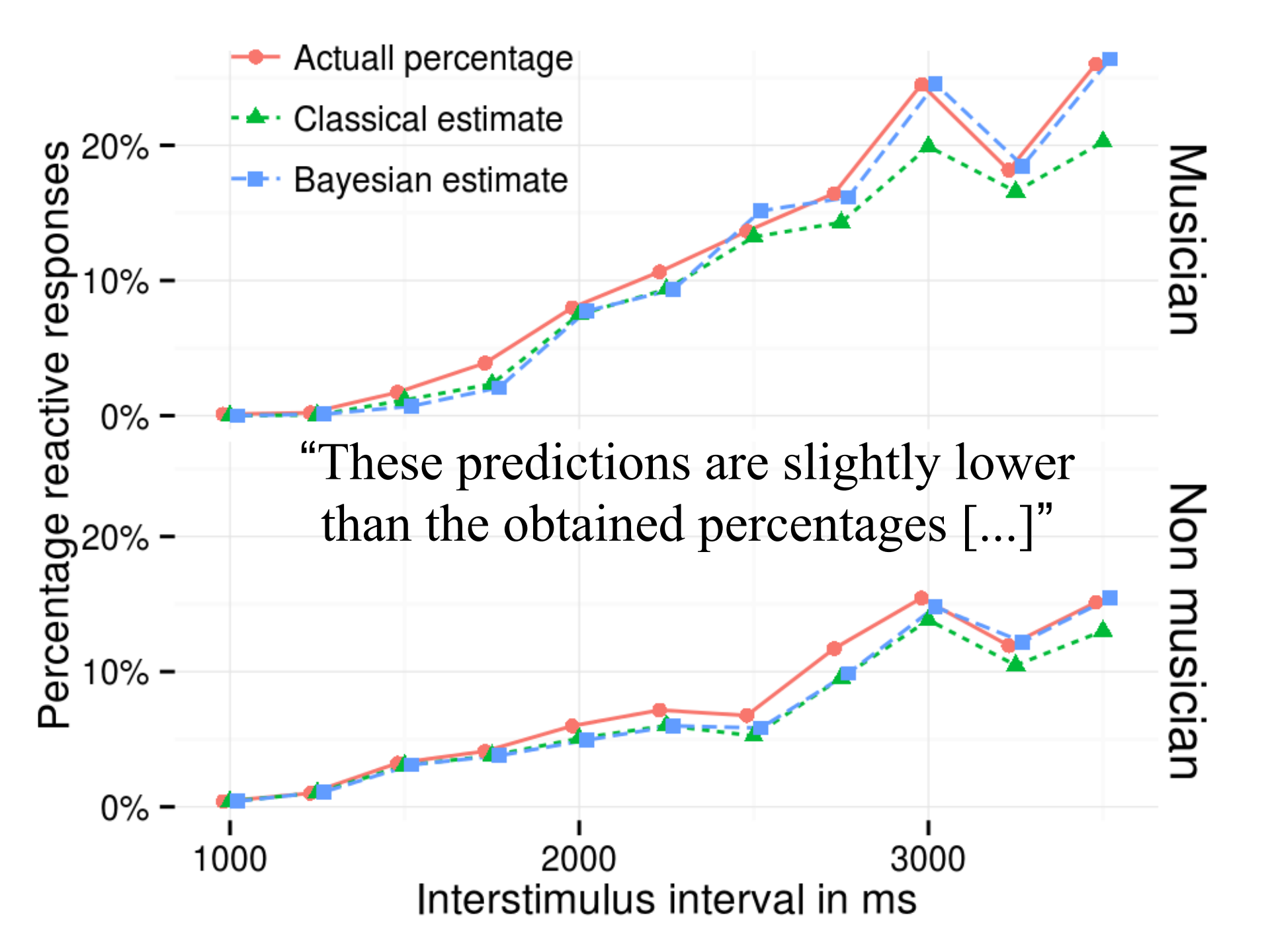

Actuall percentage
Percentage reactive responses
20%
10%
0%
Musician
Non musician
1000
2000
3000
Interstimulus interval in ms

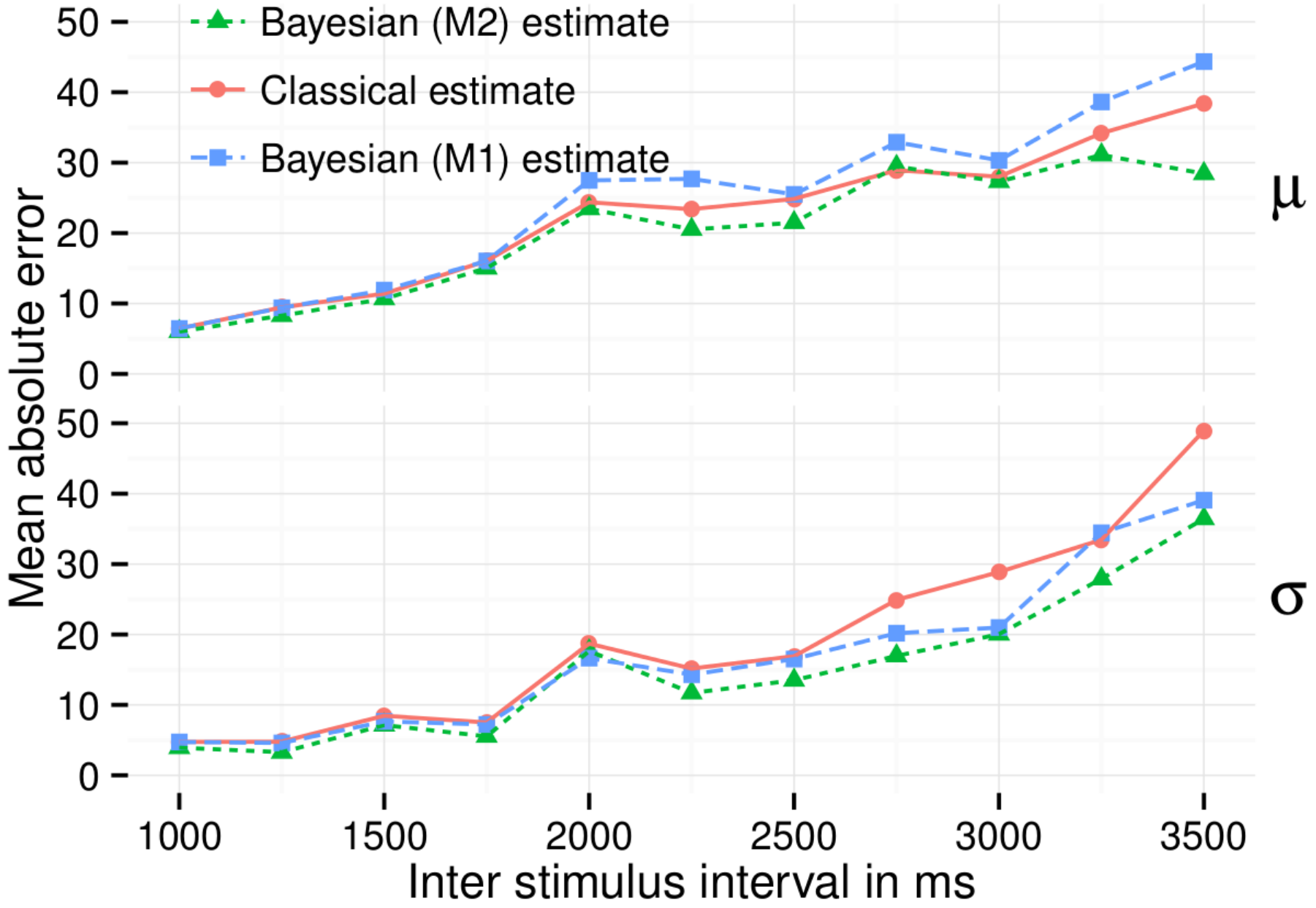

Actuall percentage
Classical estimate
Percentage reactive responses
20%
10%
0%
Musician
Non musician
1000
2000
3000
Interstimulus interval in ms

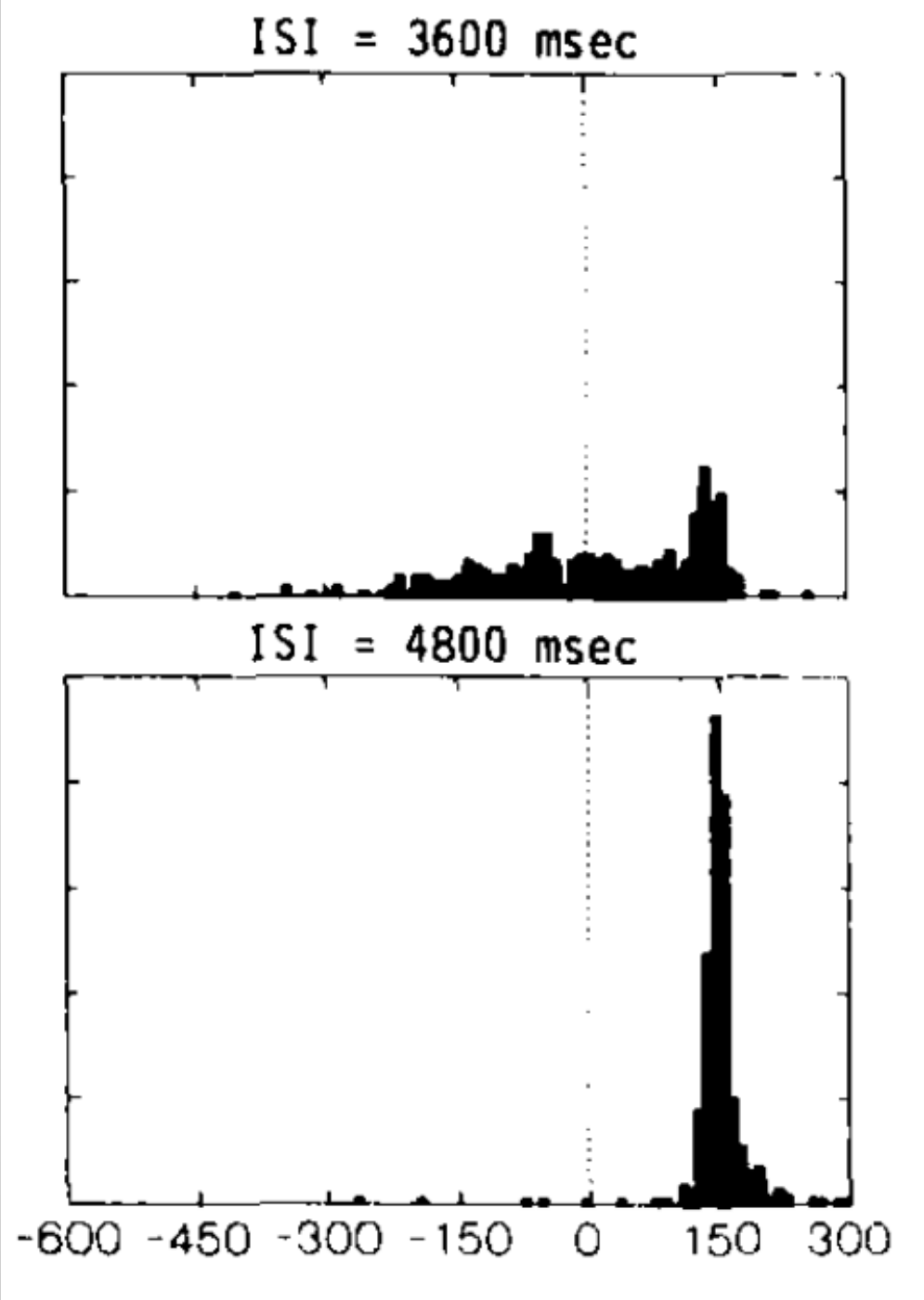


"These predictions are slightly lower than the obtained percentages [...]"

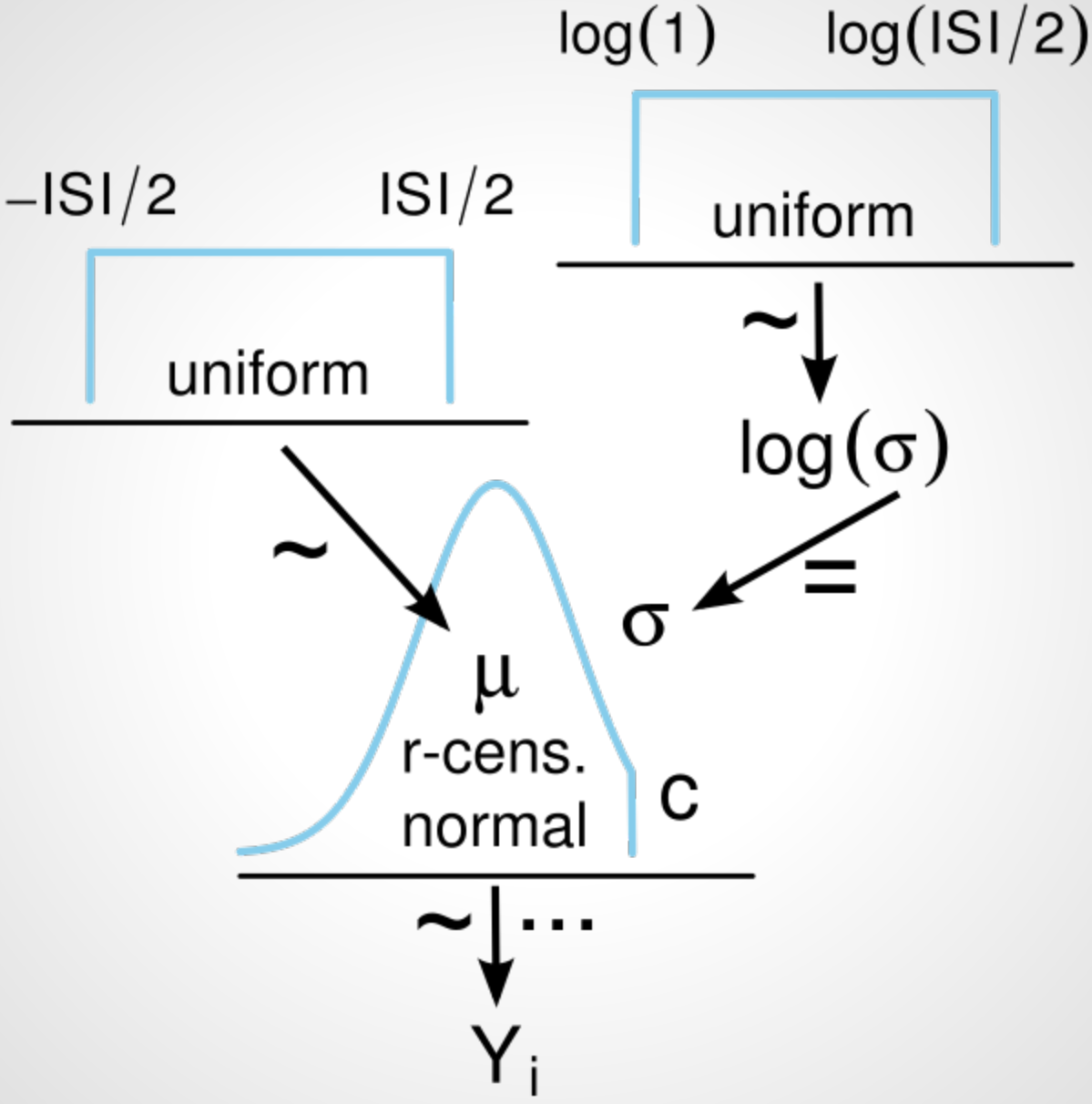


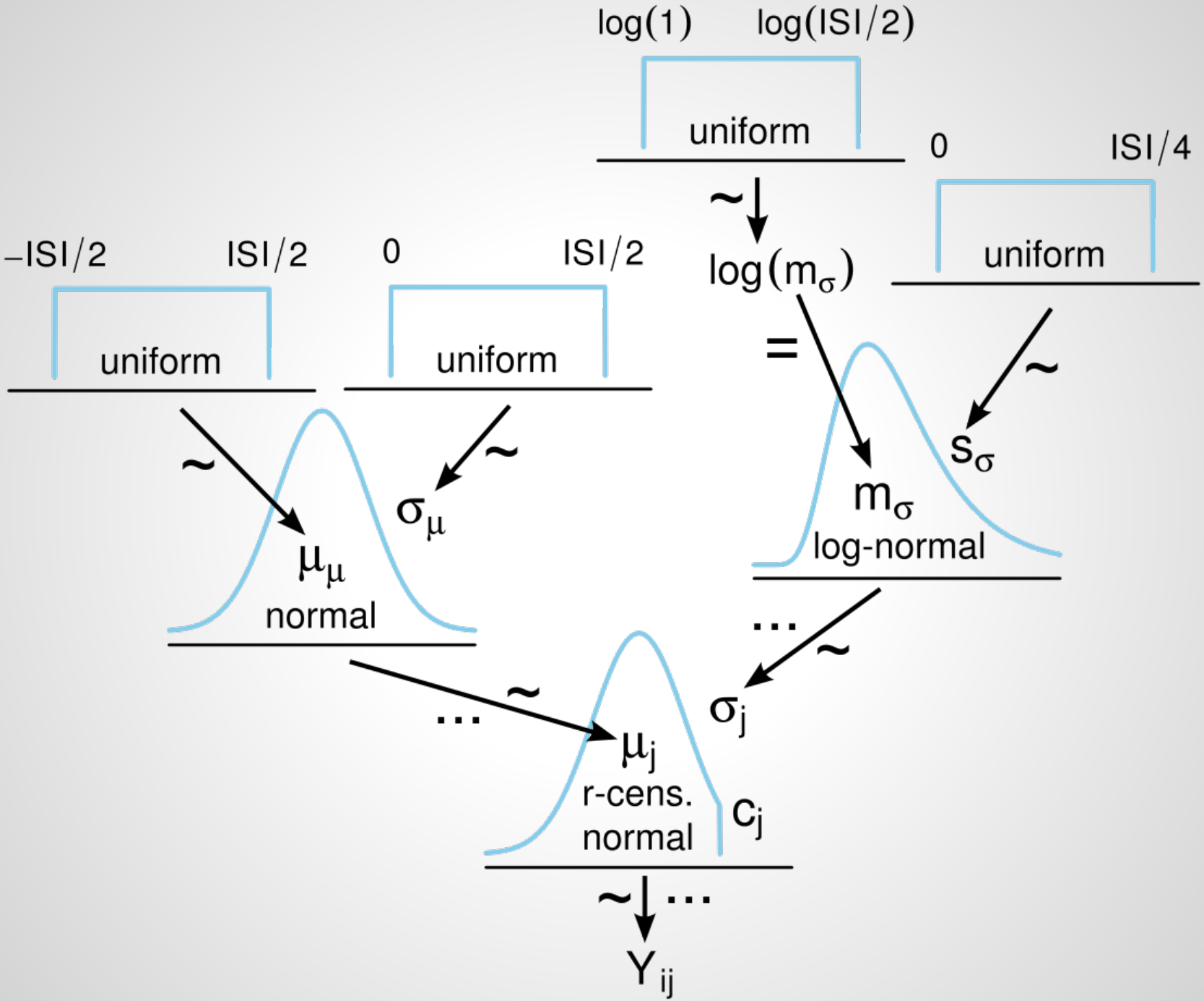
"These predictions are slightly lower than the obtained percentages [...]"

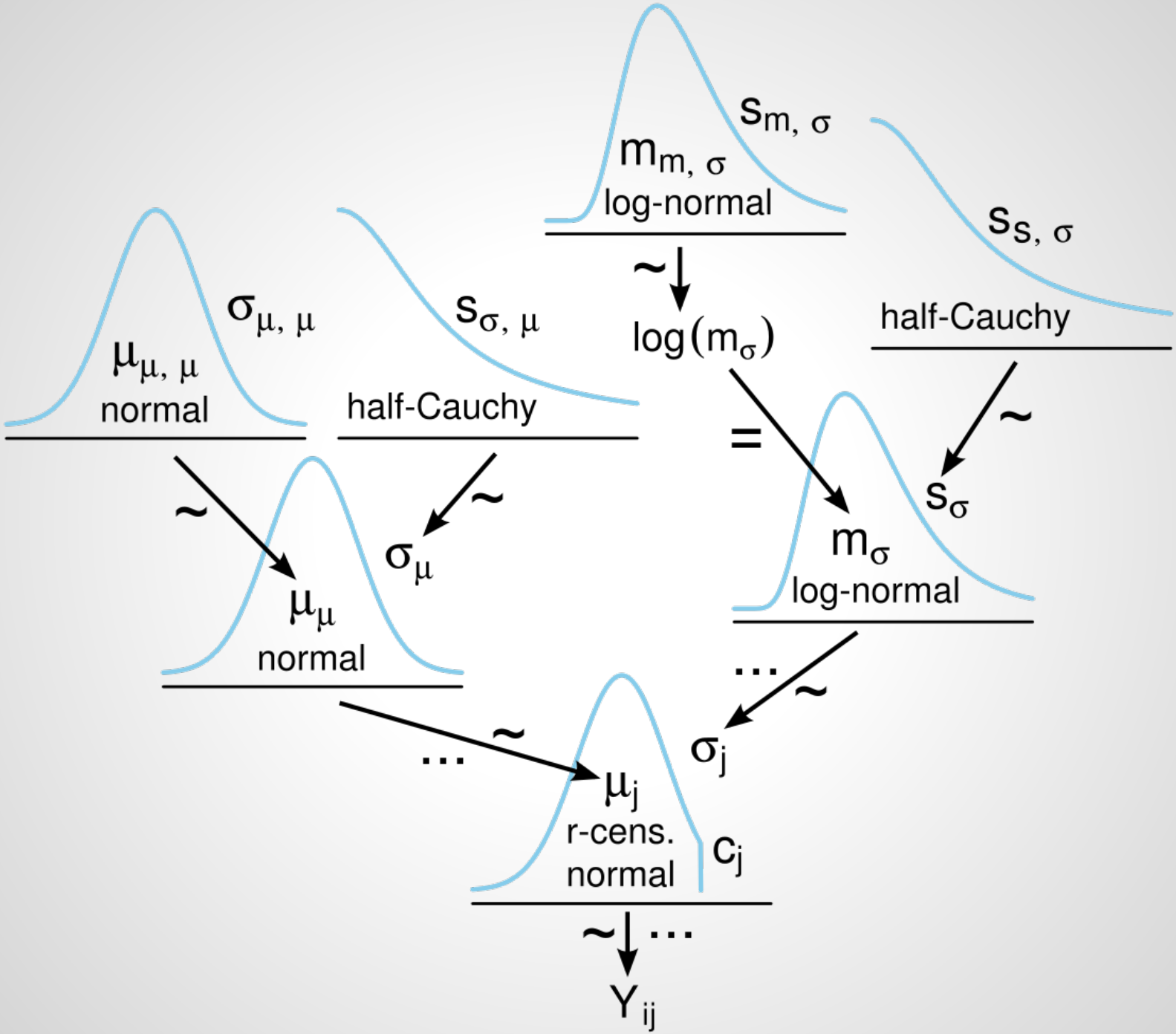

Bayesian (M2) estimate
Classical estimate
Bayesian (M1) estimate
Mean absolute error
50
40
30
20
10
0
μ
σ
1000
1500
2000
2500
3000
3500
Inter stimulus interval in ms

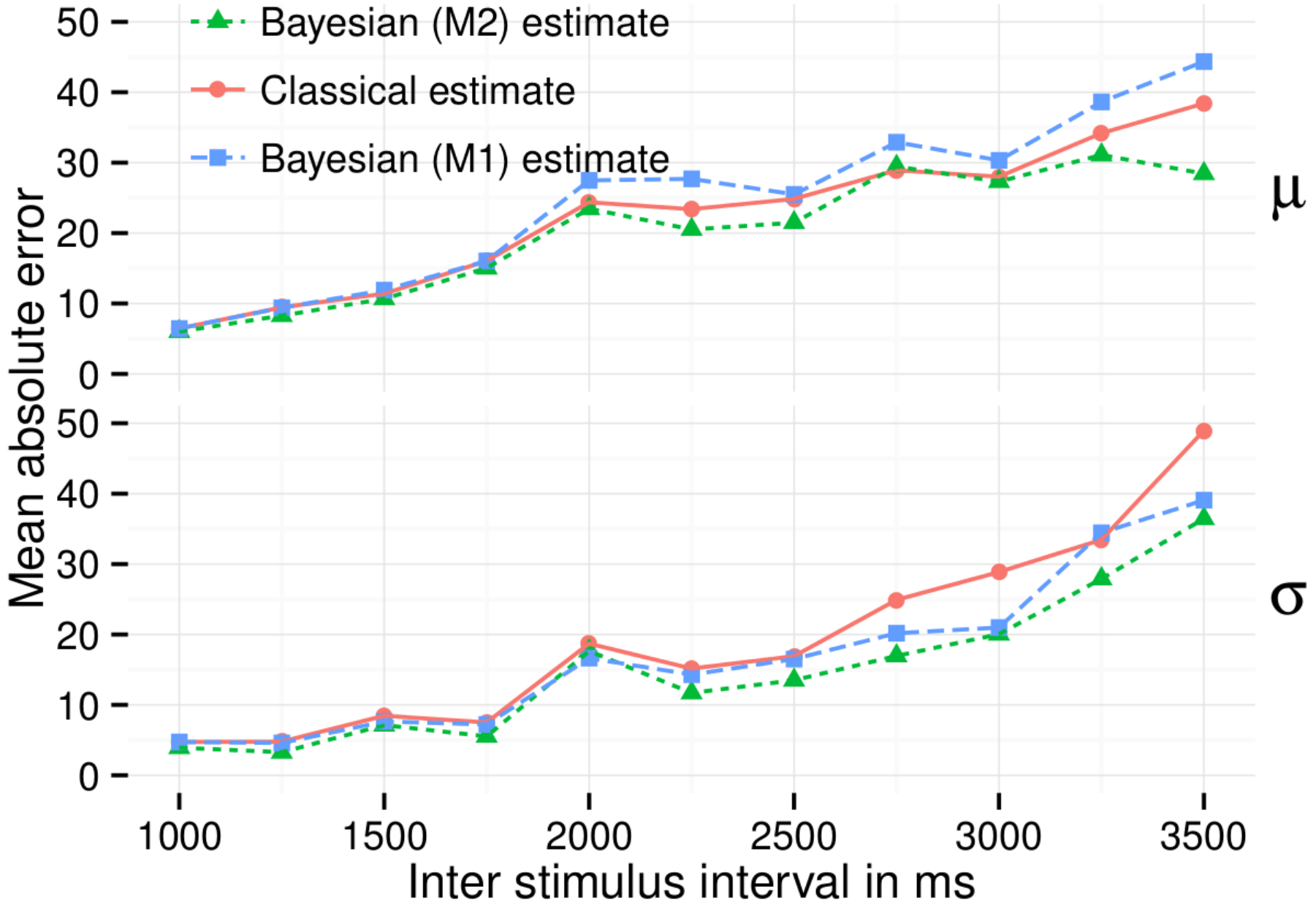


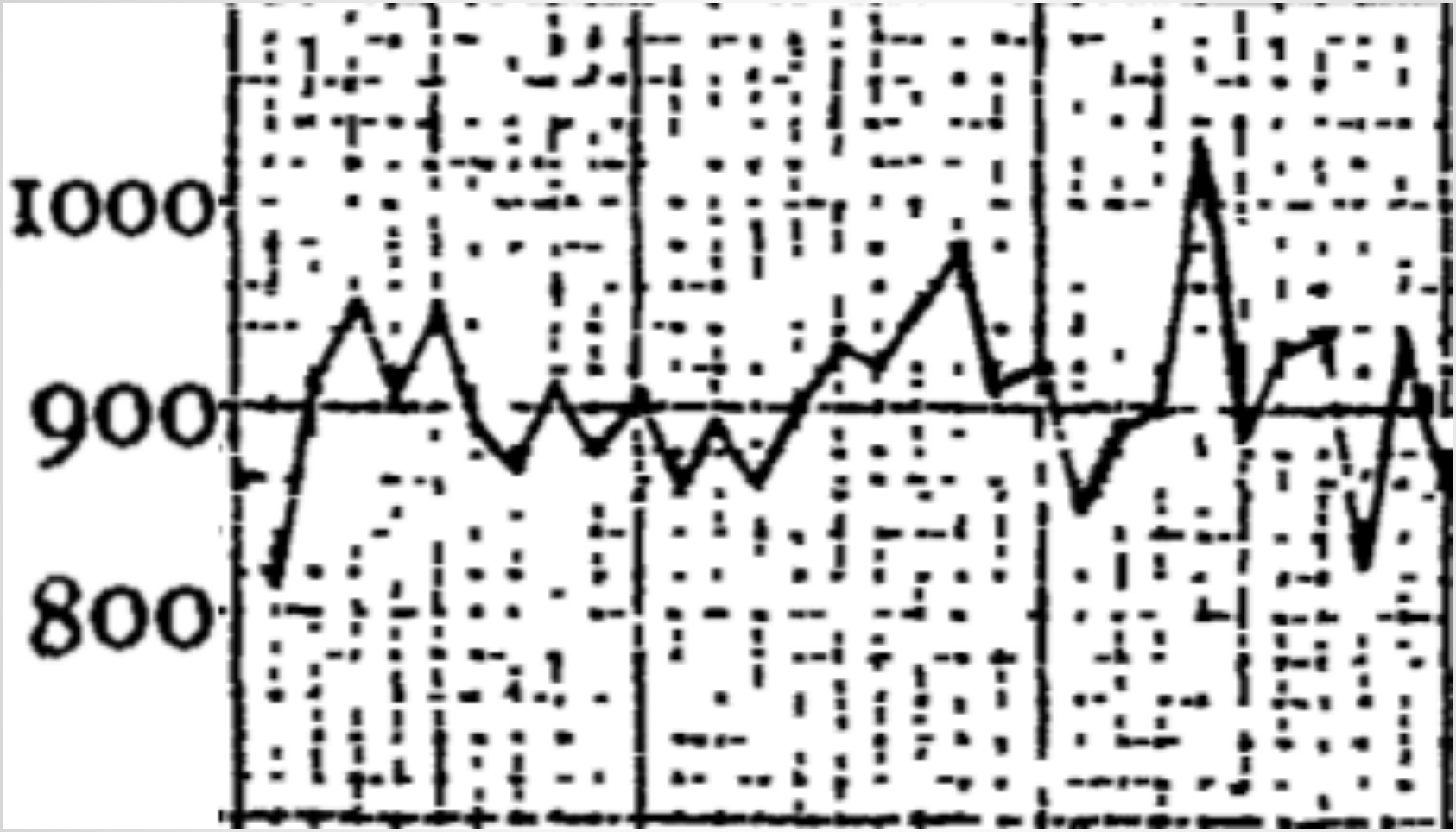
Mates, J., Müller, U., Radil, T., & Pöppel, E. (1994)


log(1)
log(ISI/2)
uniform
~
log(σ)
=
σ
–ISI/2
ISI/2
uniform
~
μ
r-cens.
normal
c
~
...
Y i

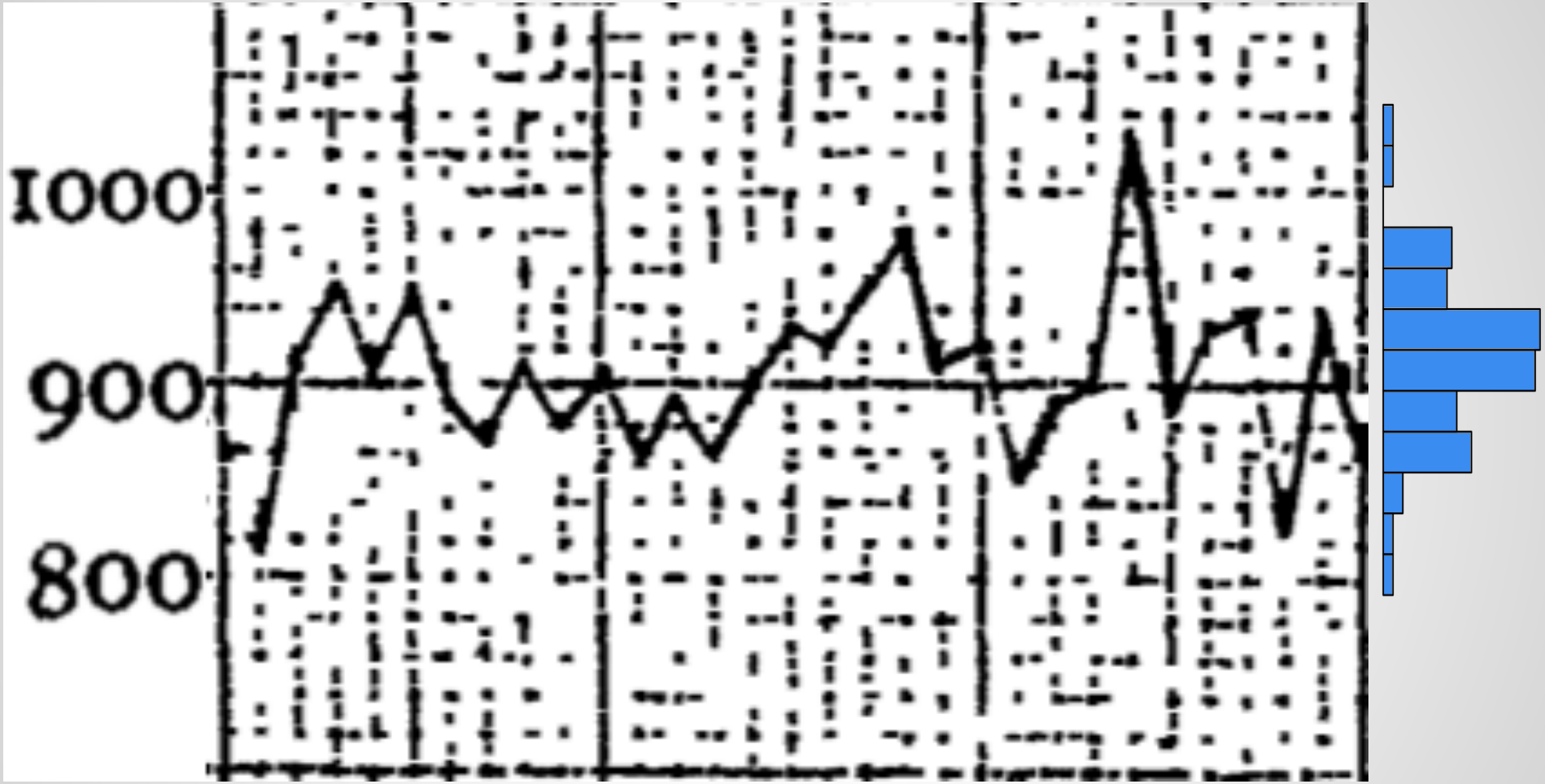

log(1)
log(ISI/2)
uniform
0
ISI/4
uniform
~
log(m_σ)
=
–ISI/2
ISI/2
uniform
0
ISI/2
uniform
~
~
s_σ
~
σ_μ
m_σ
log-normal
μ_μ
normal
...
~
~
σ_j
...
~
μ_j
r-cens.
normal
c_j
~
...
Y_ij


$s_{m,\sigma}$
$m_{m,\sigma}$
log-normal
$s_{s,\sigma}$
half-Cauchy
$\sigma_{\mu,\mu}$
$\mu_{\mu,\mu}$
normal
$s_{\sigma,\mu}$
half-Cauchy
$\log(m_\sigma)$
s_σ
σ_μ
m_σ
log-normal
μ_μ
normal
σ_j
μ_j
r-cens.
normal
c_j
Y_{ij}

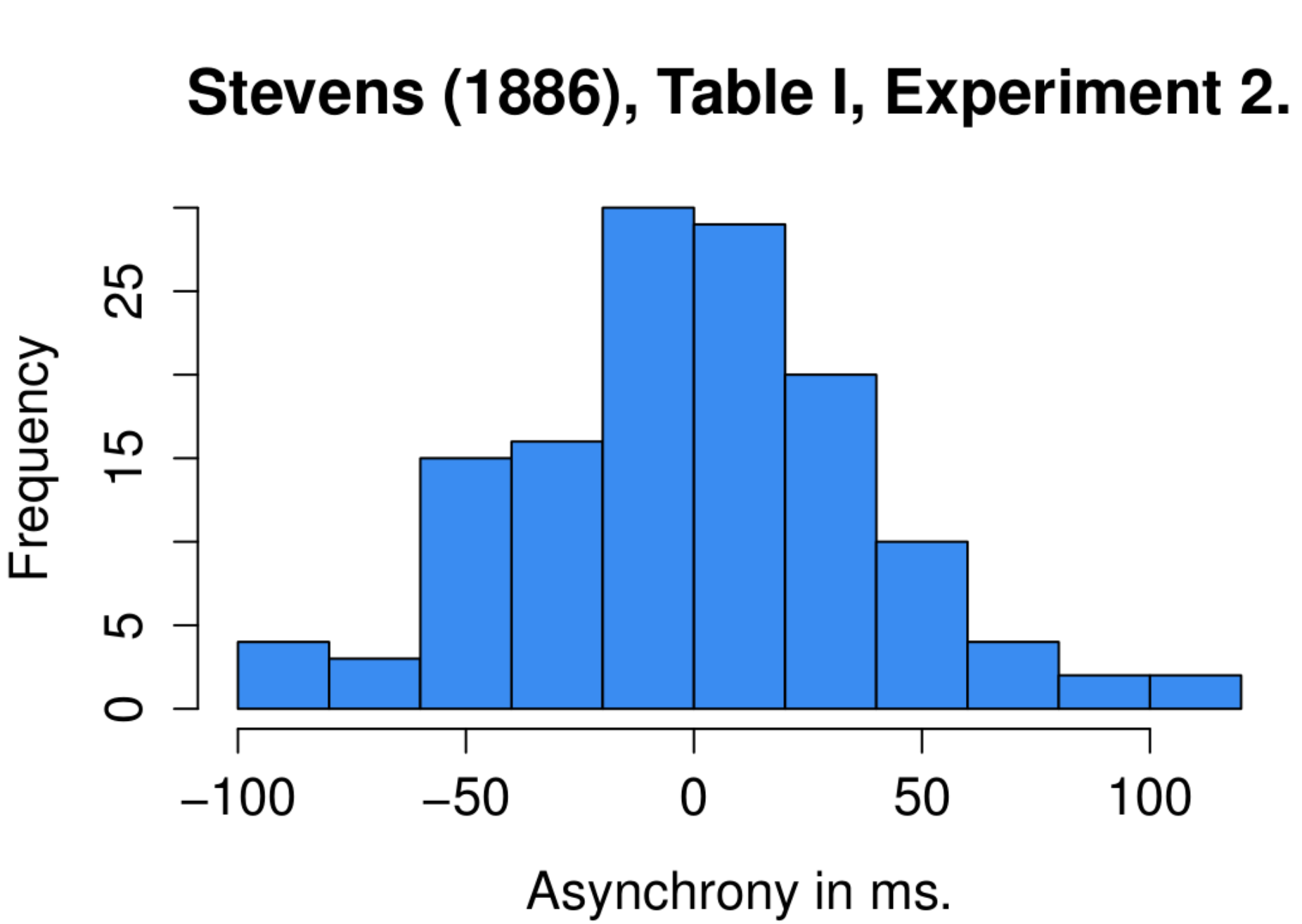

Bayesian (M2) estimate
Classical estimate
Bayesian (M1) estimate
Mean absolute error
50
40
30
20
10
0
μ
σ
1000
1500
2000
2500
3000
3500
Inter stimulus interval in ms



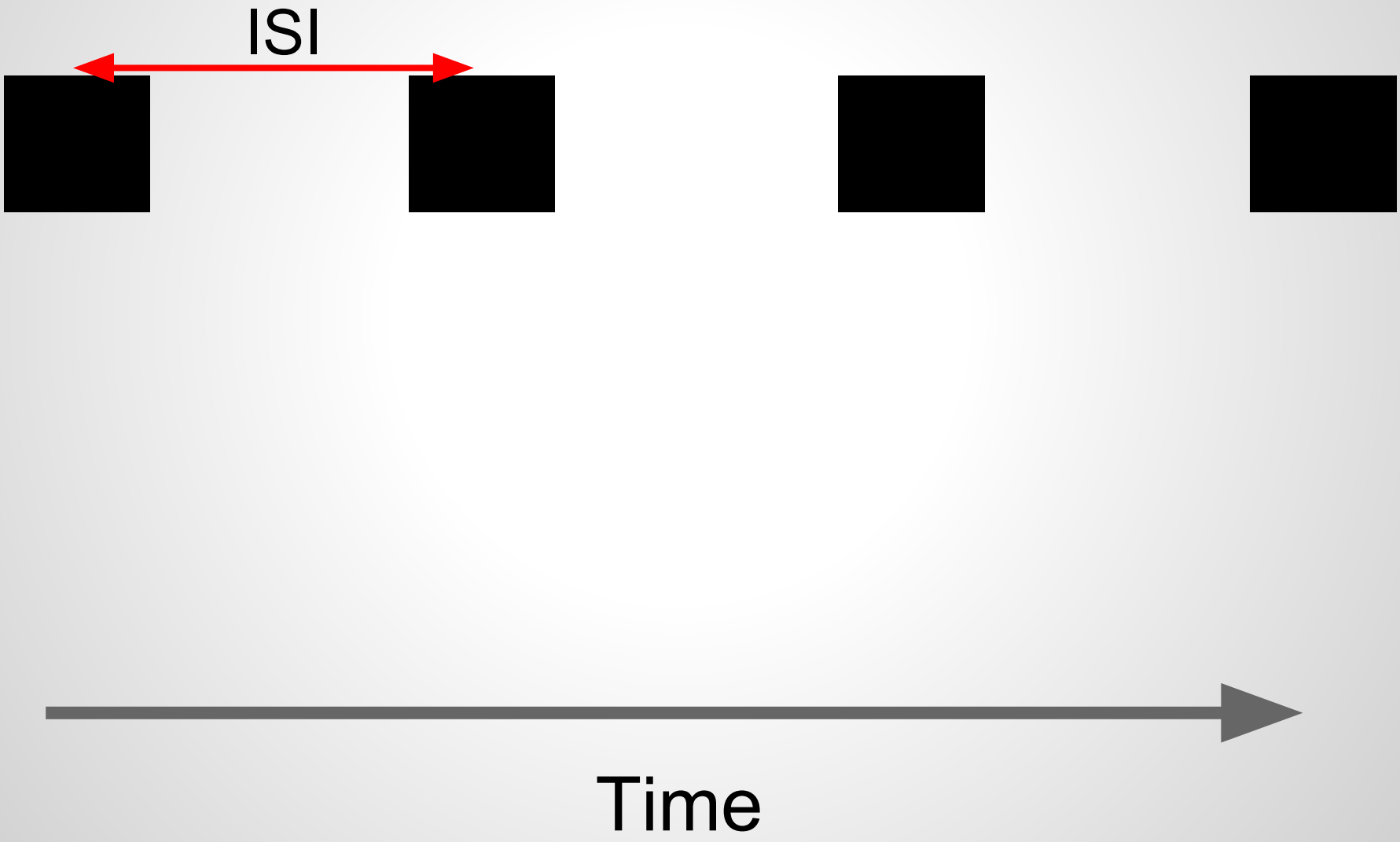
Stevens, L. T. (1886). On The Time-Sense.



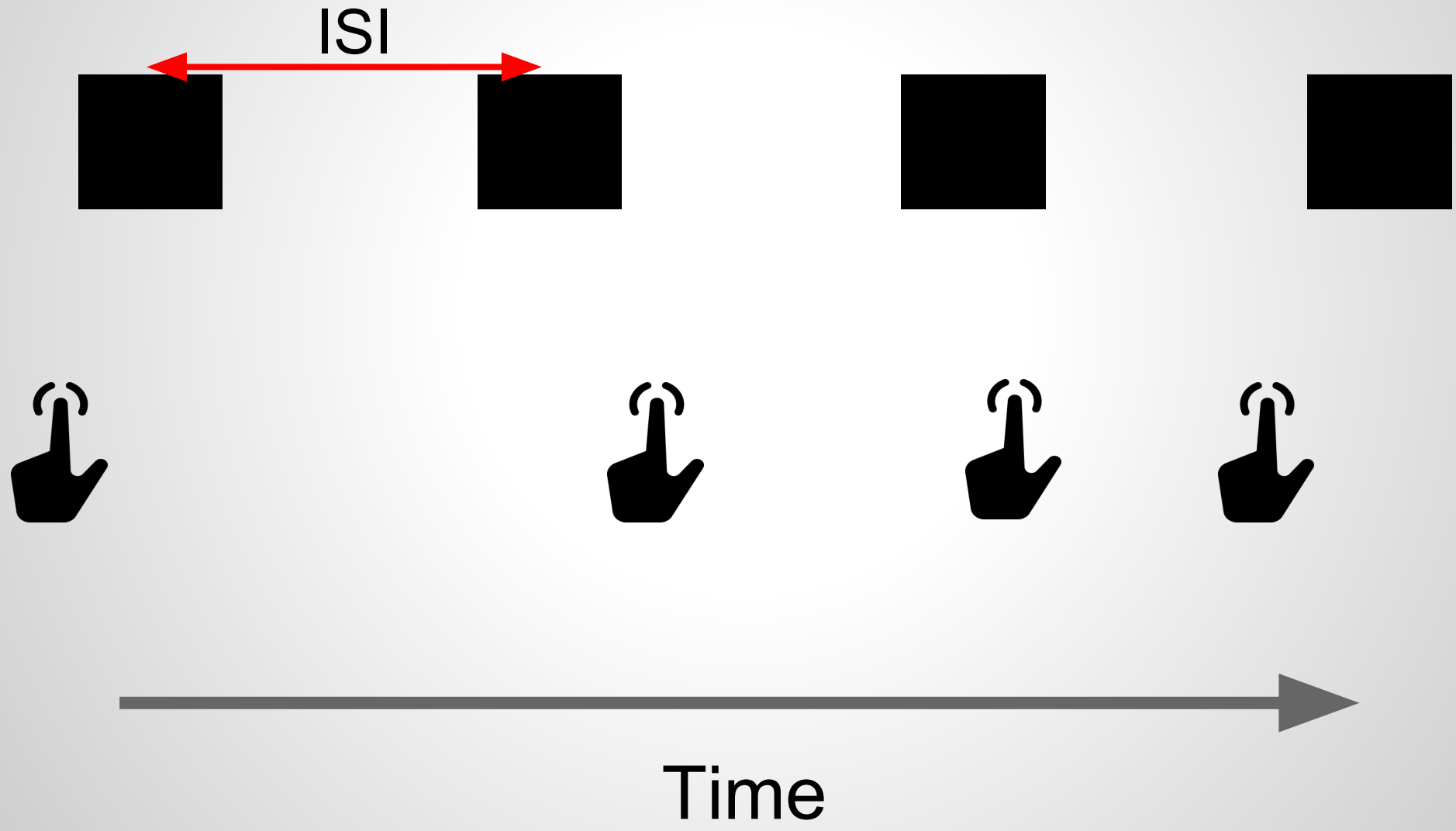
Stevens, L. T. (1886). On The Time-Sense.


Stevens (1886), Table I, Experiment 2.
Frequency
0
5
15
25
−100
−50
0
50
100
Asynchrony in ms.

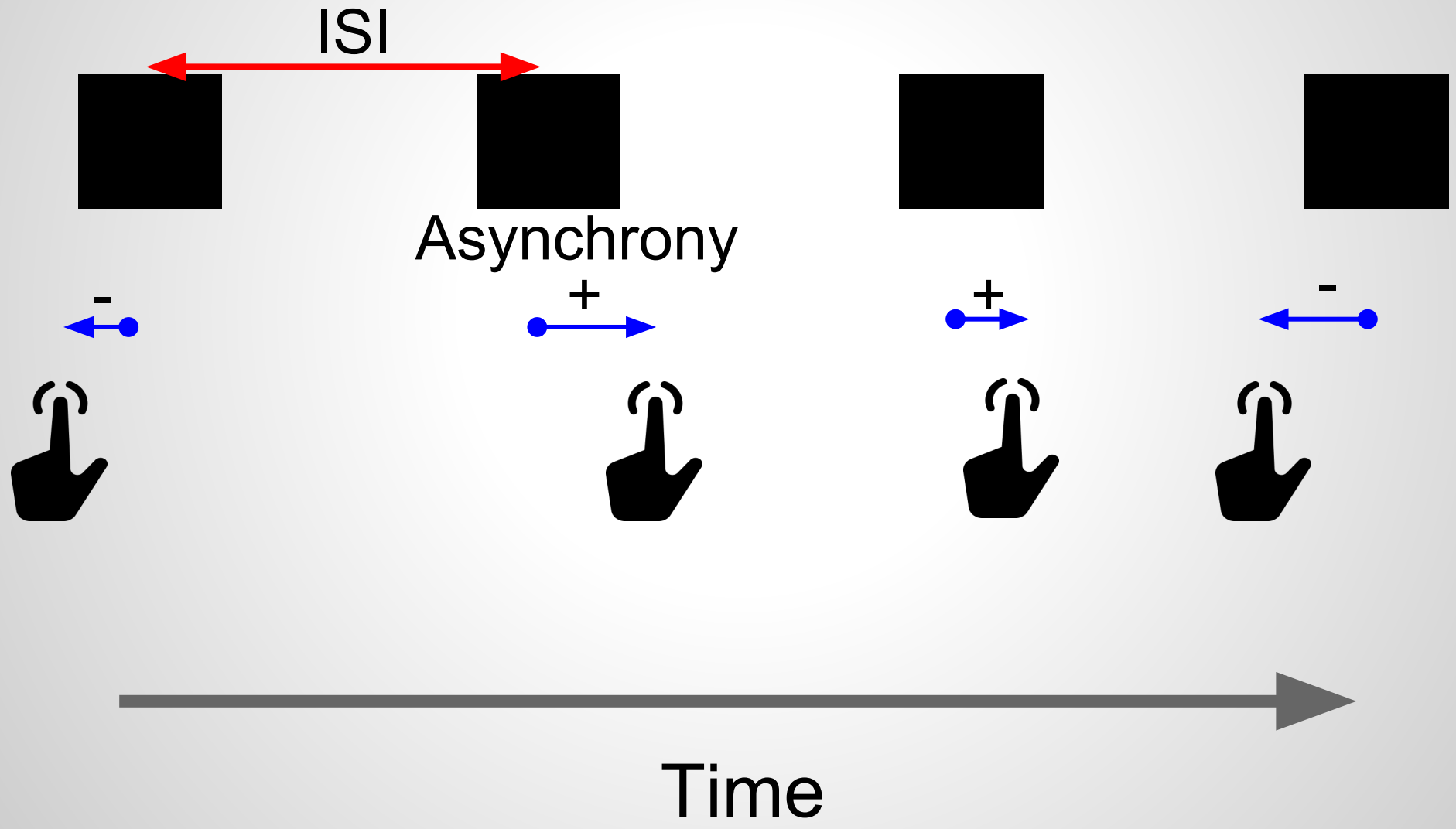
The Basic Sensorimotor Synchronization task

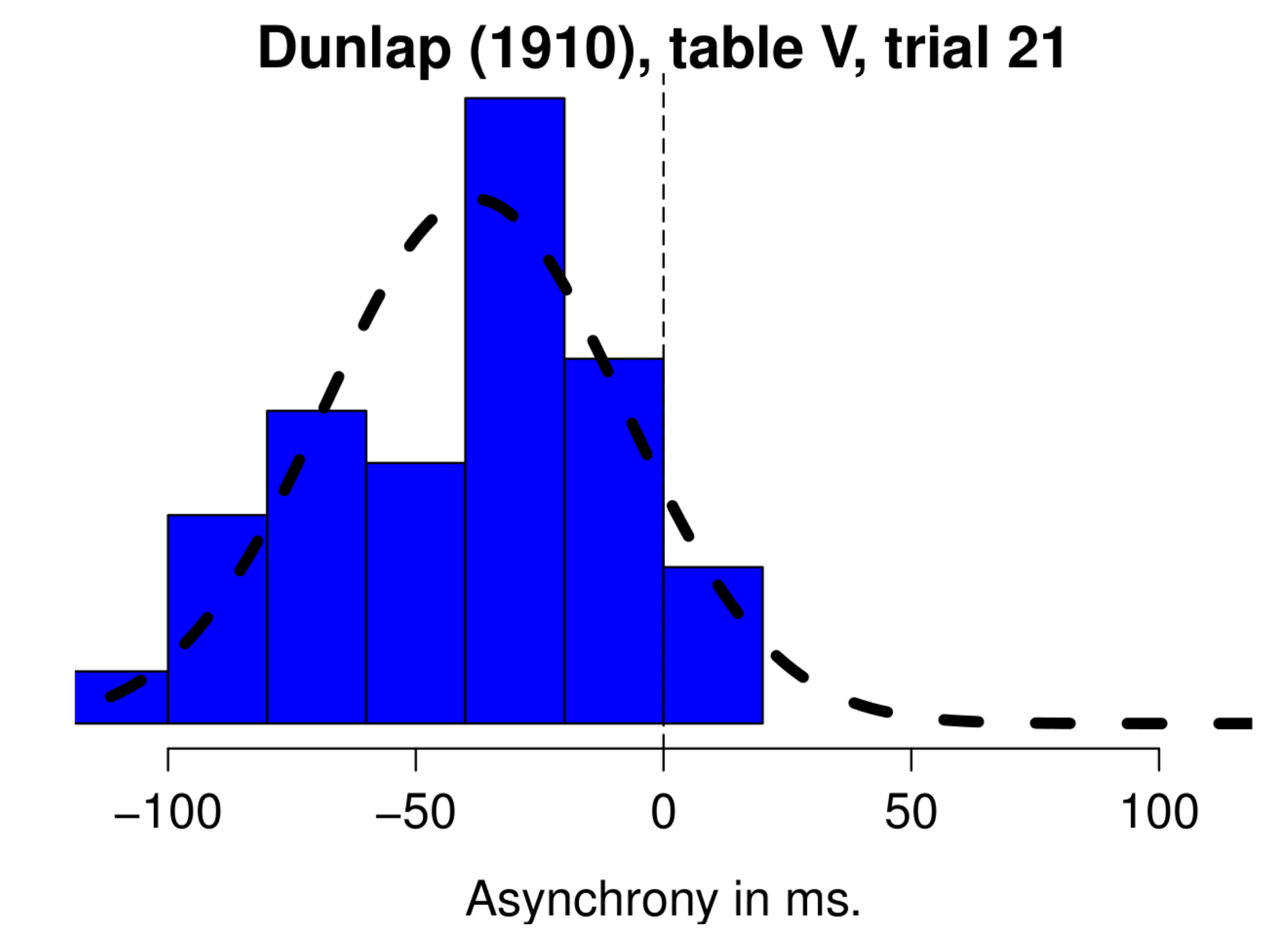


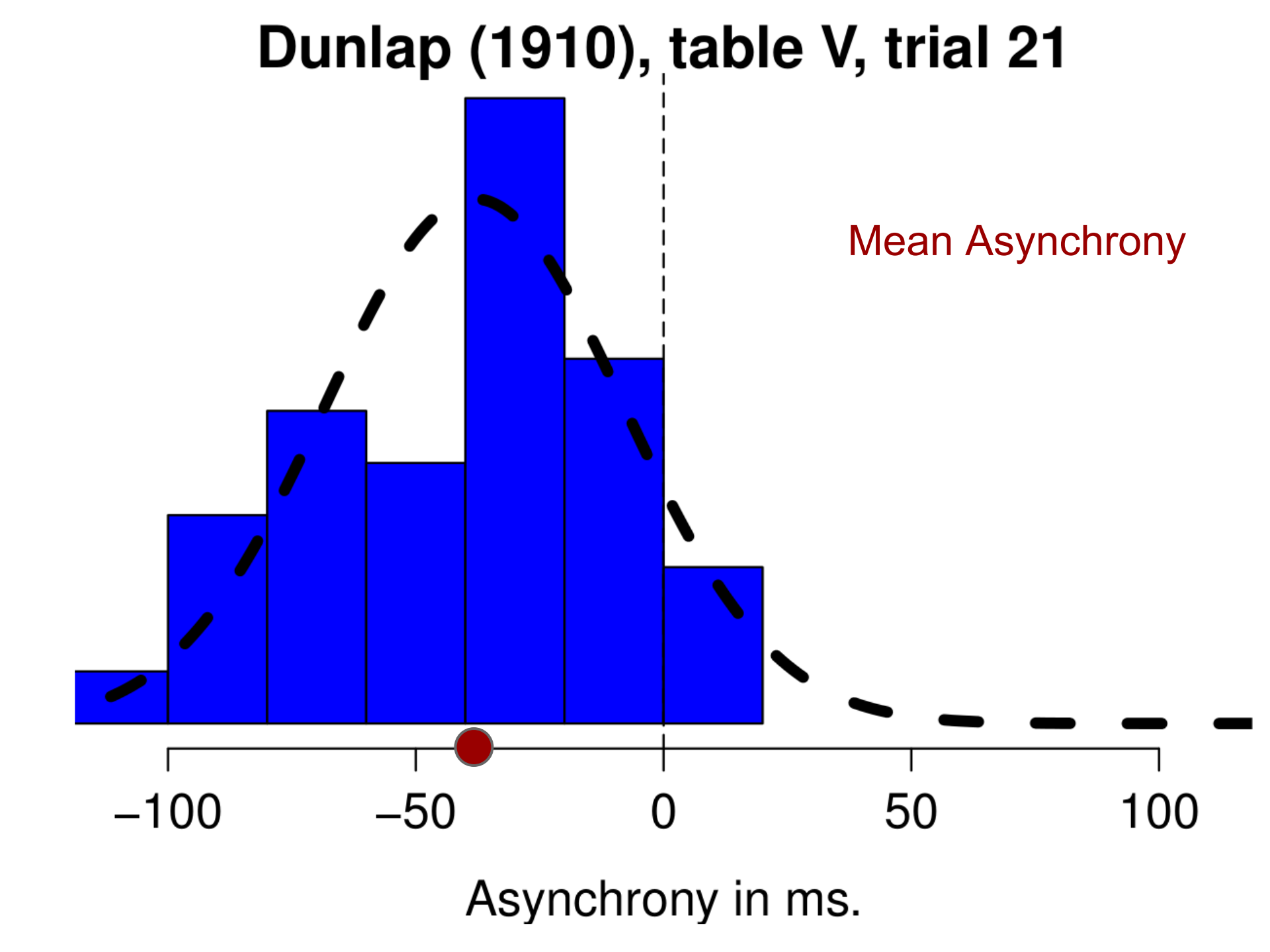
The Basic Sensorimotor Synchronization task

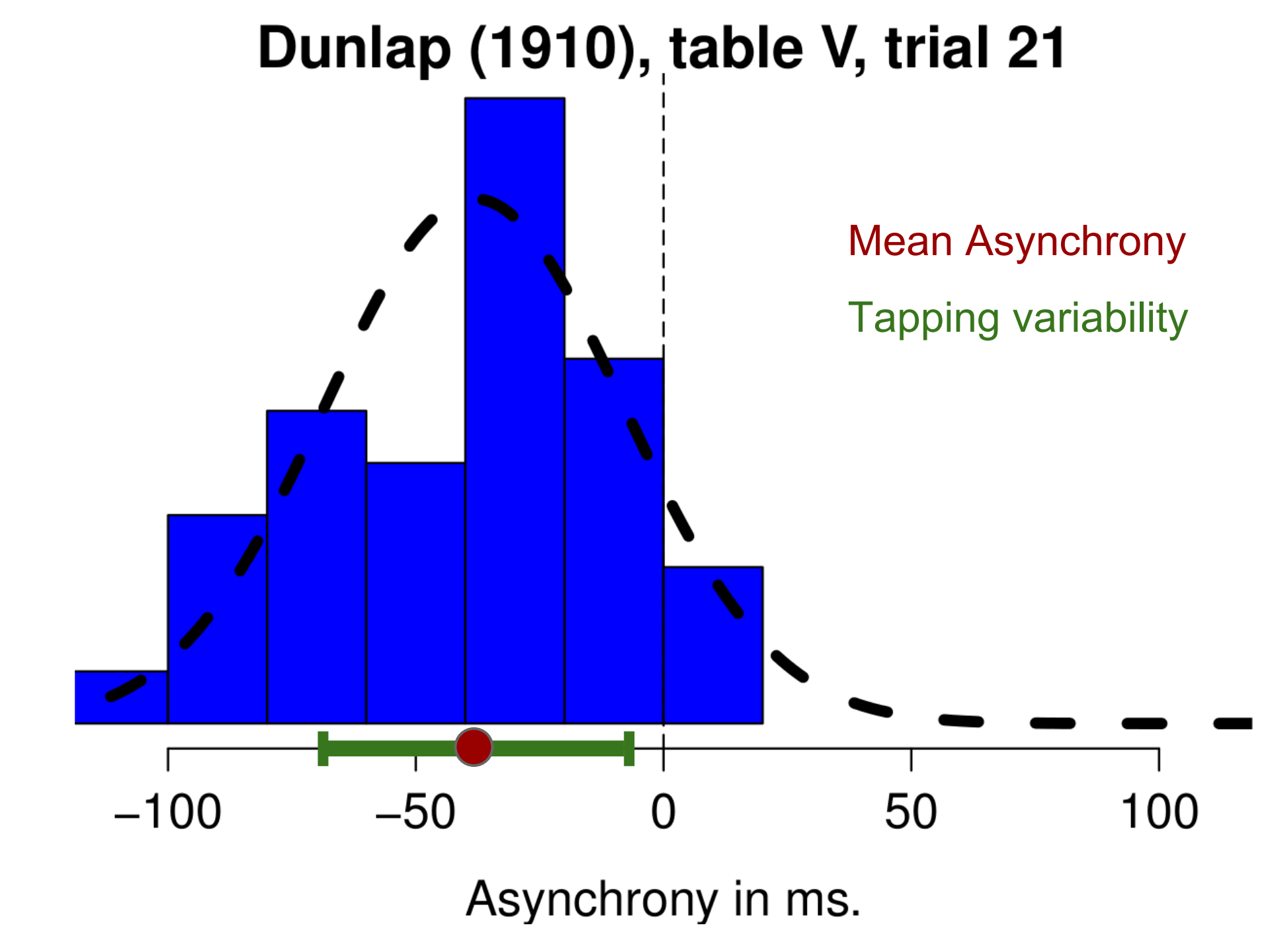


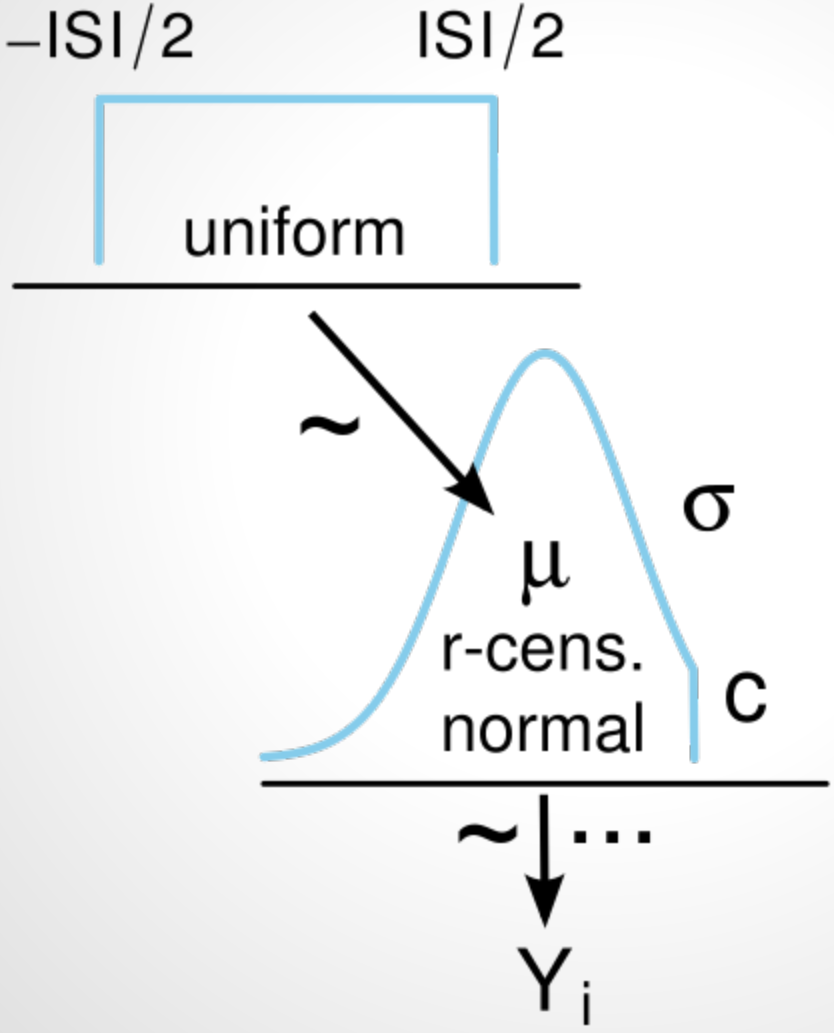
The Basic Sensorimotor Synchronization task

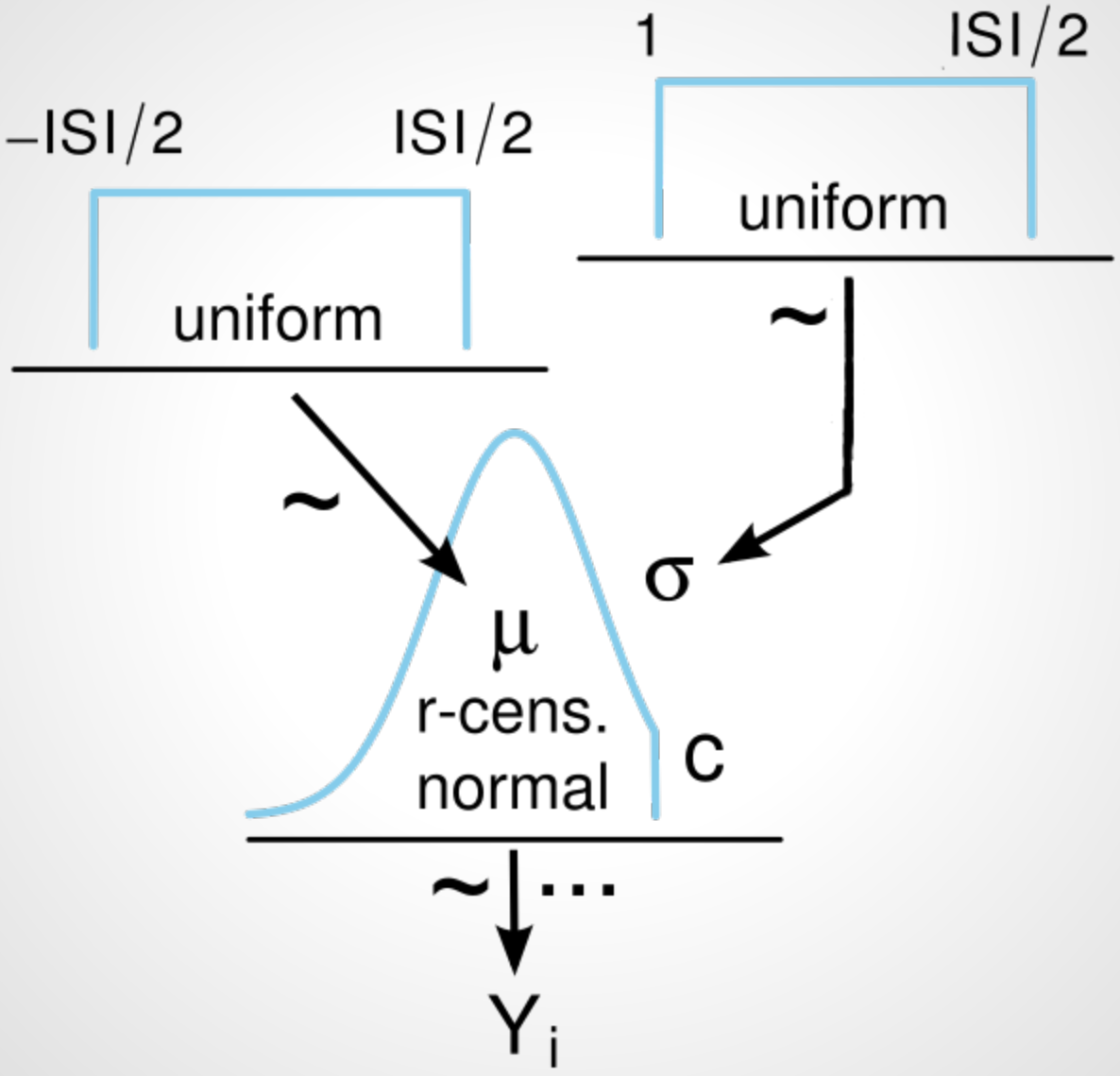


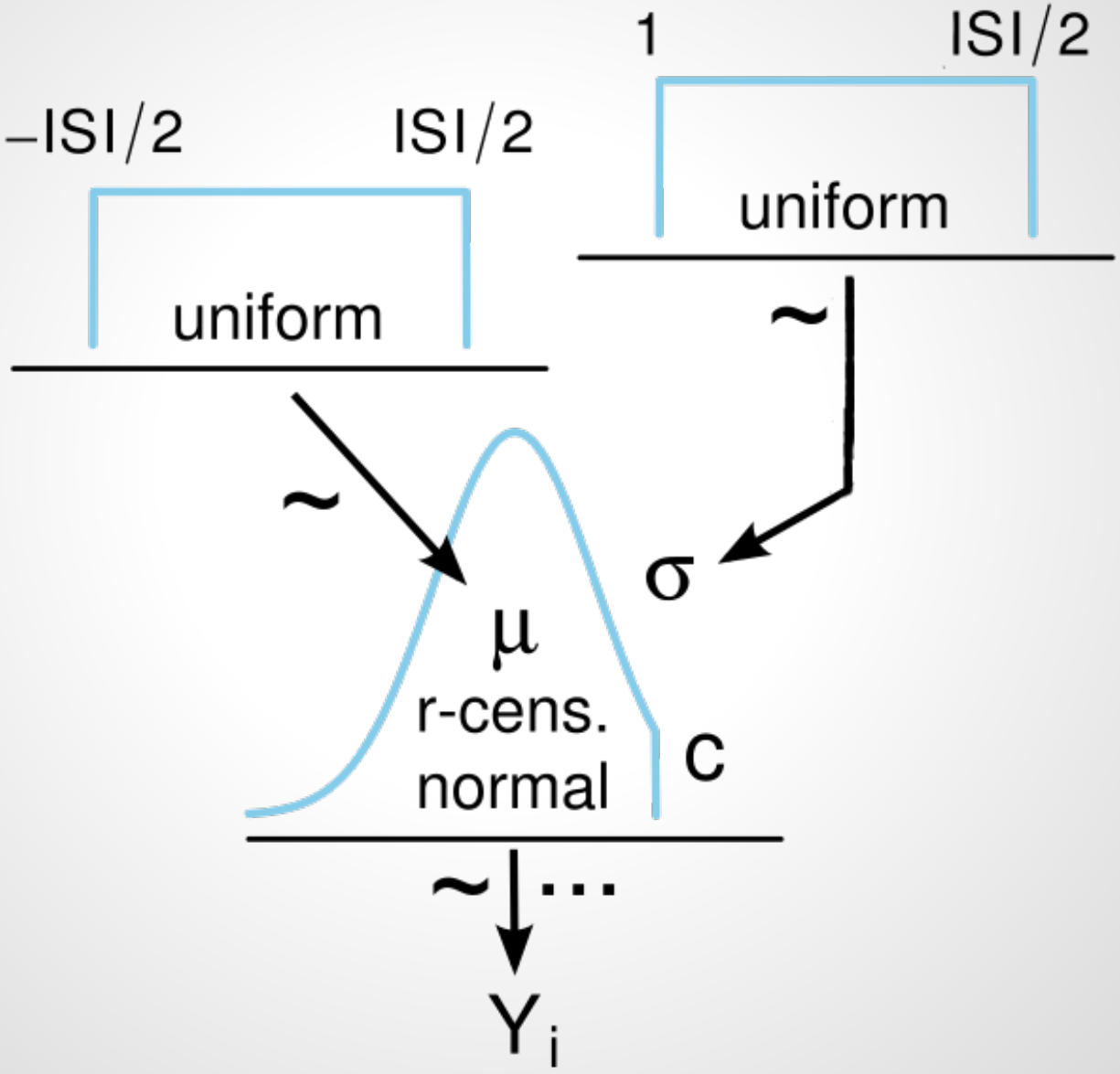

Dunlap (1910), table V, trial 21
−100
−50
0
50
100
Asynchrony in ms.

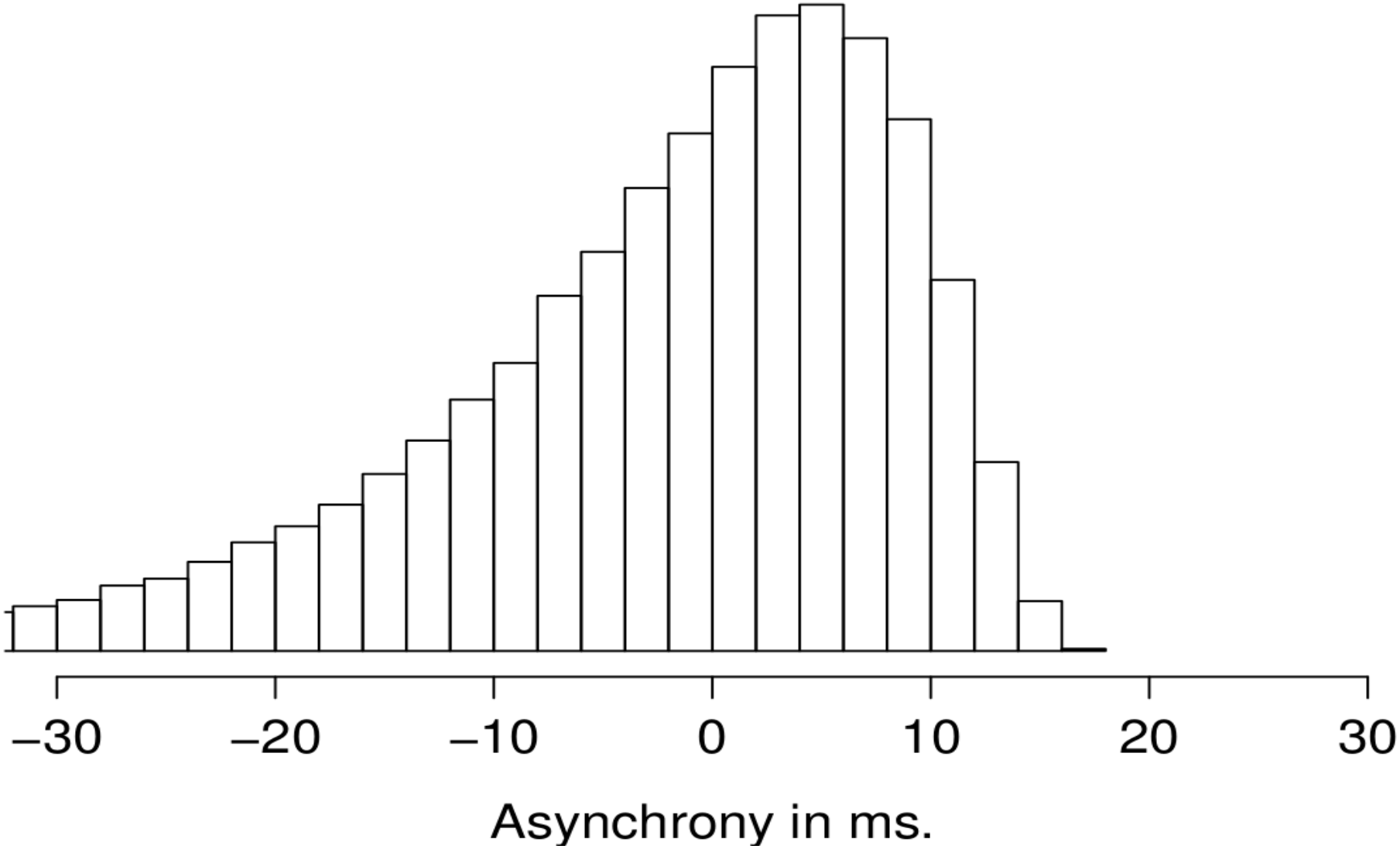

Dunlap (1910), table V, trial 21
Mean Asynchrony
–100
–50
0
50
100
Asynchrony in ms.

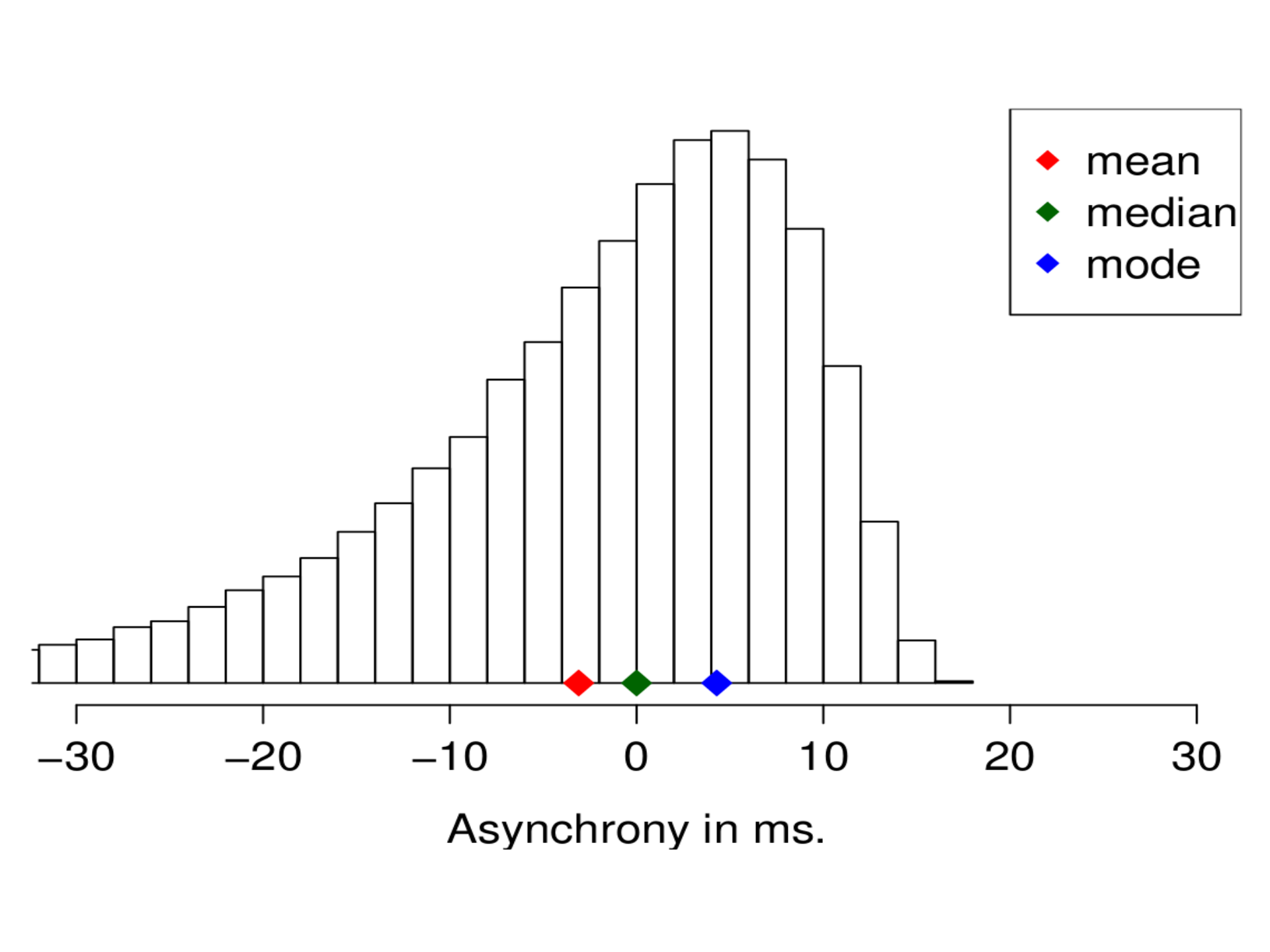

Dunlap (1910), table V, trial 21
Mean Asynchrony
Tapping variability
–100
–50
0
50
100
Asynchrony in ms.


–ISI/2
ISI/2
uniform
~
σ
μ
r-cens.
normal
c
~
...
Y i


1
|SI/2
–|SI/2
|SI/2
uniform
uniform
~
~
σ
μ
r-cens.
normal
c
~
...
Y i


1
ISI/2
–ISI/2
ISI/2
uniform
uniform
~
~
σ
μ
r-cens.
normal
c
~
...
Y i


−30
−20
−10
0
10
20
30
Asynchrony in ms.


mean
median
mode
−30
−20
−10
0
10
20
30
Asynchrony in ms.