NeuroImaging Data Processing

aka. Statistical Parametric Mapping short course

<u>Course 5:</u>

Evoked response fMRI & Design efficiency

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Content

- Block/epoch vs. event-related fMRI
- (Dis)Advantages of efMRI
- GLM: Convolution
- BOLD impulse response
- Temporal Basis Functions
- Timing Issues
- Design Optimisation – “Efficiency”

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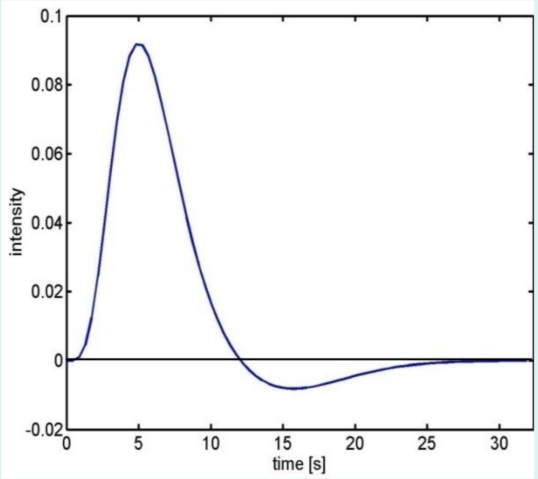
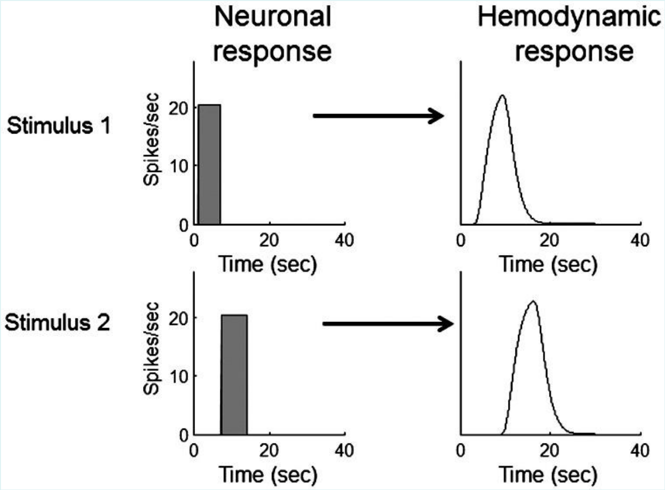
BOLD response

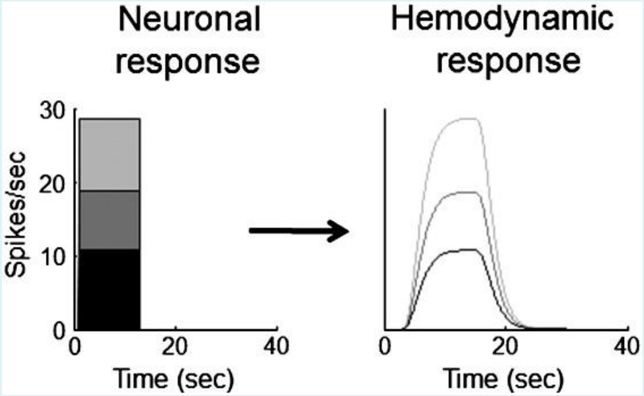
Hemodynamic response function (HRF):



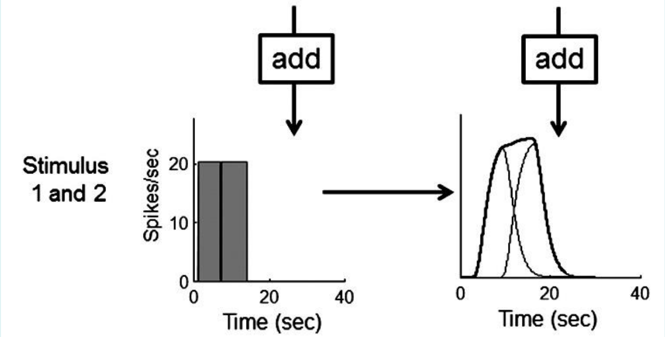
Shift invariance



Scaling



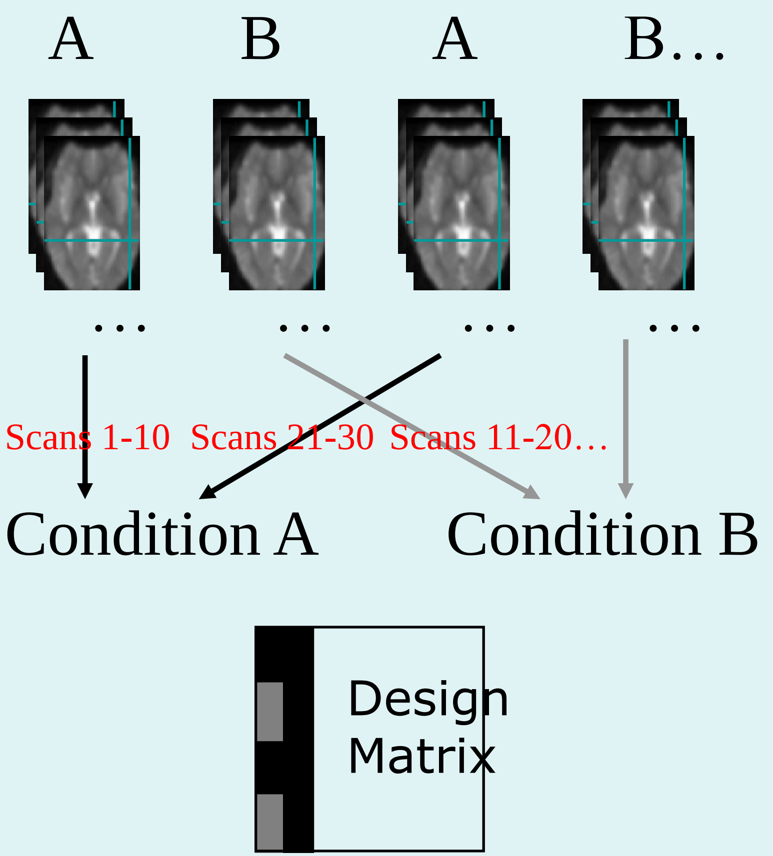
Additivity



Boynton et al, NeuroImage, 2012.

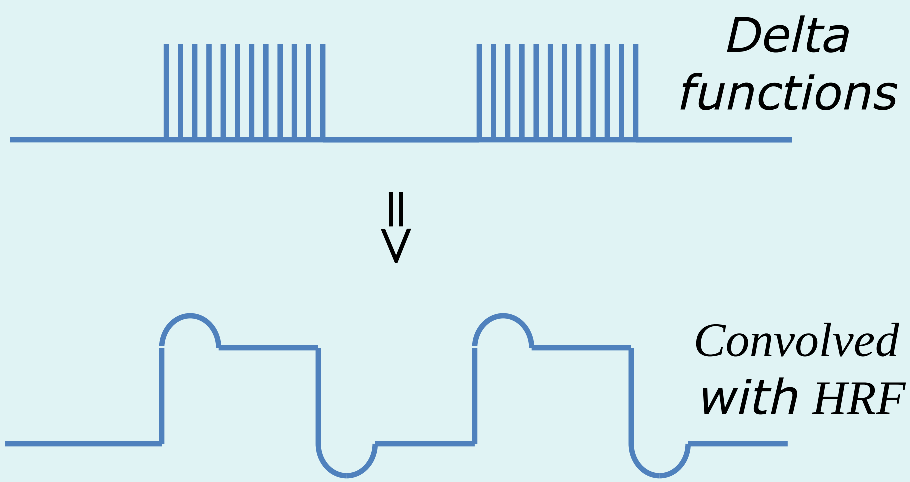
Epoch vs. event related design

"PET Blocked conception"
(scans assigned to conditions)



"fMRI Epoch conception"
(scans treated as timeseries)

"fMRI Event-related conception"

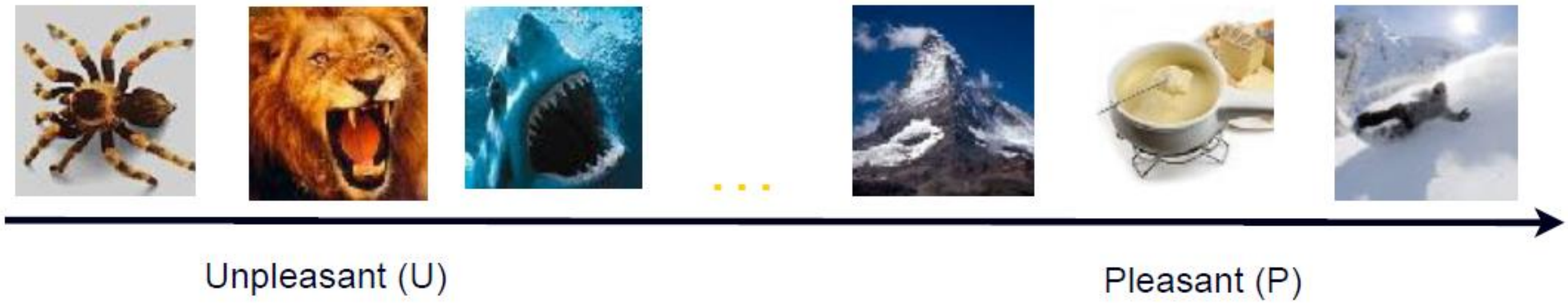


Advantages of Event-Related design

- Randomised trial order

  c.f. confounds of blocked designs

Blocked designs may trigger expectations and cognitive sets



Intermixed designs can minimise this by stimulus randomisation

Advantages of Event-Related design

- Randomised trial order

  c.f. confounds of blocked designs

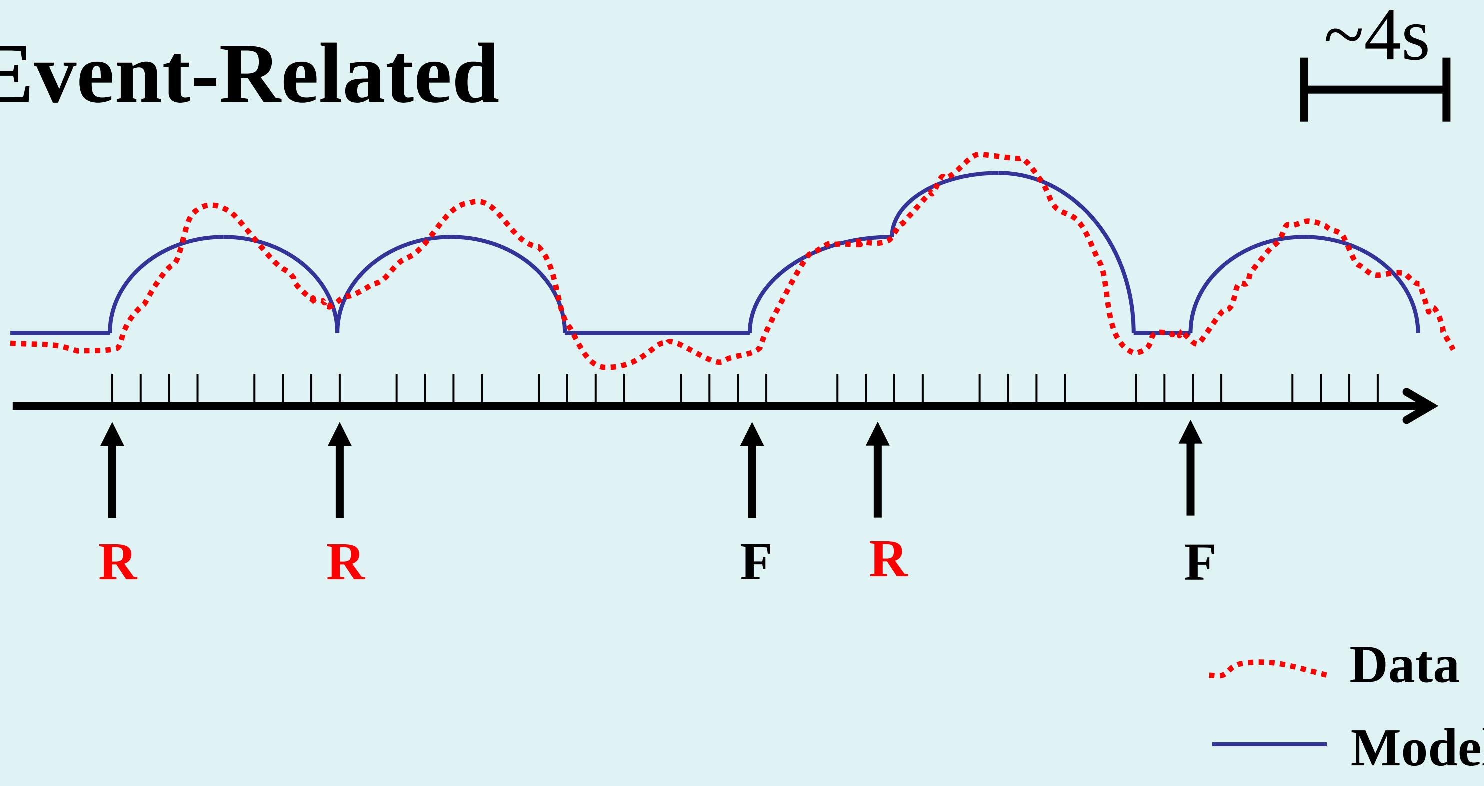
- Post hoc / subjective classification of trials

  e.g, according to subsequent memory

R = Words Later Remembered

F = Words Later Forgotten

Event-Related



Advantages of Event-Related design

- Randomised trial order
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- Post hoc / subjective classification of trials
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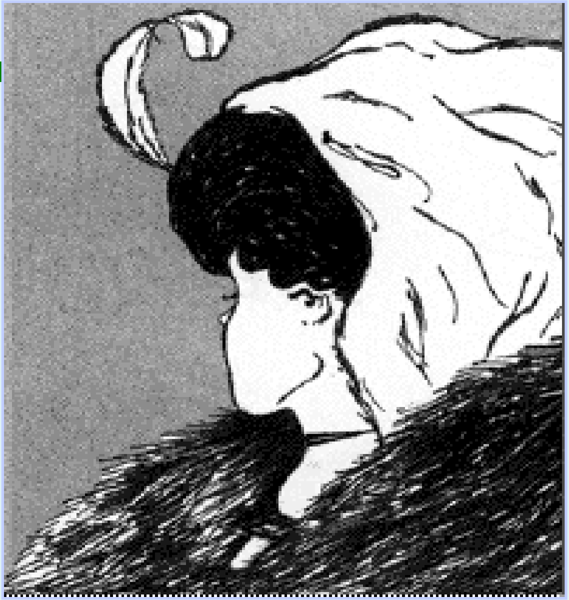
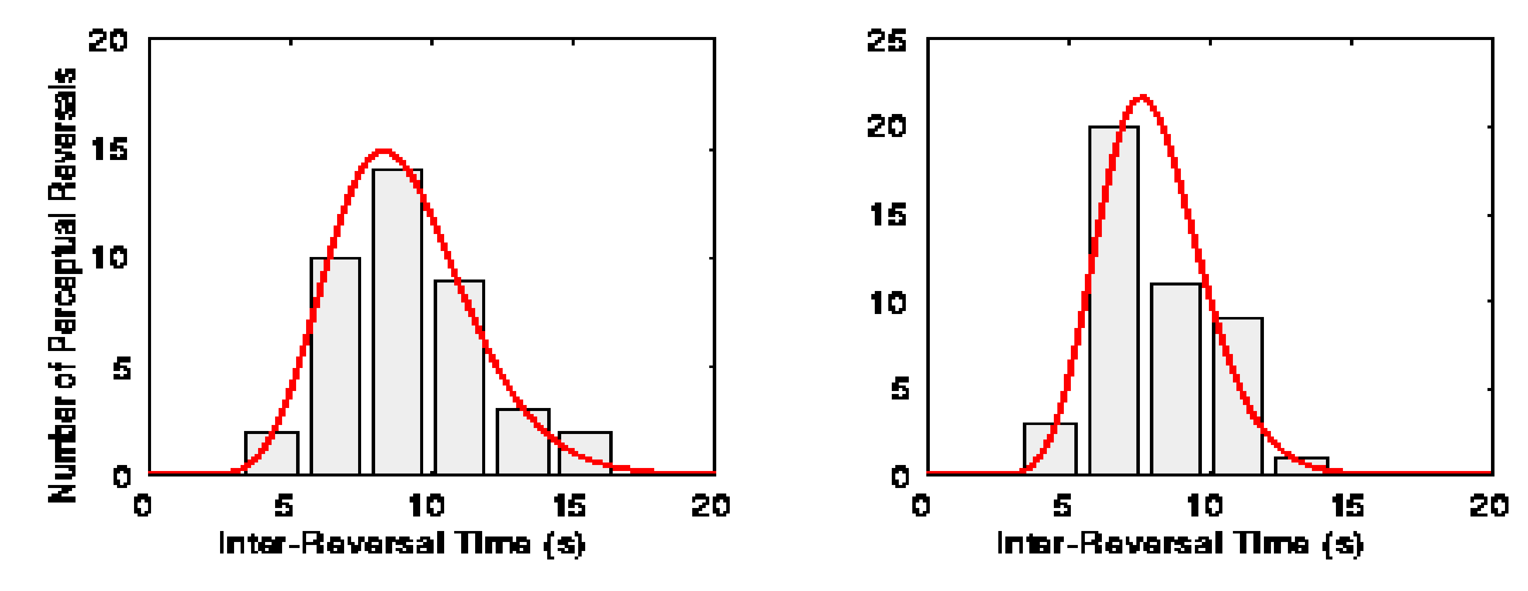
- Some events can only be indicated (in time)
  e.g, spontaneous perceptual changes





Number of Perceptual Reversals
0
5
10
15
20
0
5
10
15
20
Inter-Reversal Time (s)
0
5
10
15
20
25
0
5
10
15
20
Inter-Reversal Time (s)

Advantages of Event-Related design

- Randomised trial order

  c.f. confounds of blocked designs

- Post hoc / subjective classification of trials

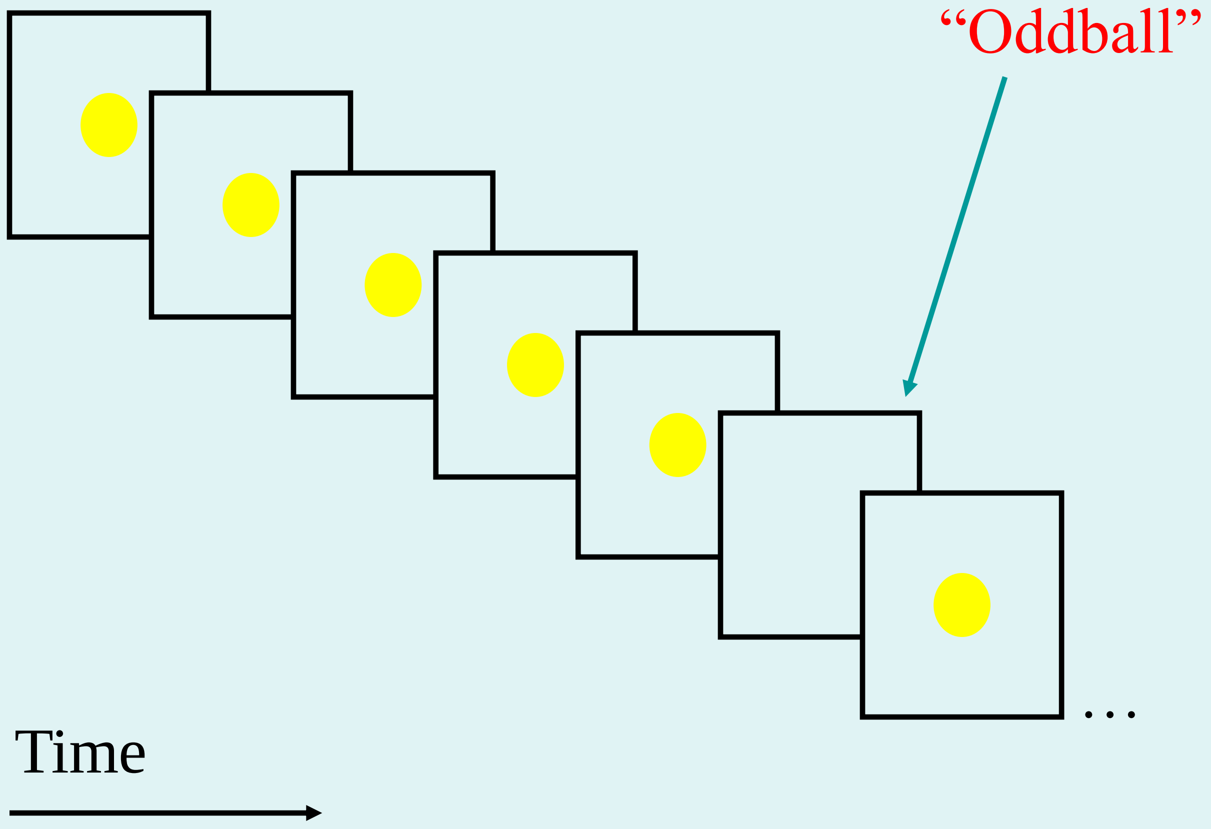
  e.g, according to subsequent memory

- Some events can only be indicated (in time)

  e.g, spontaneous perceptual changes

- Some trials cannot be blocked

  e.g, "oddball" designs



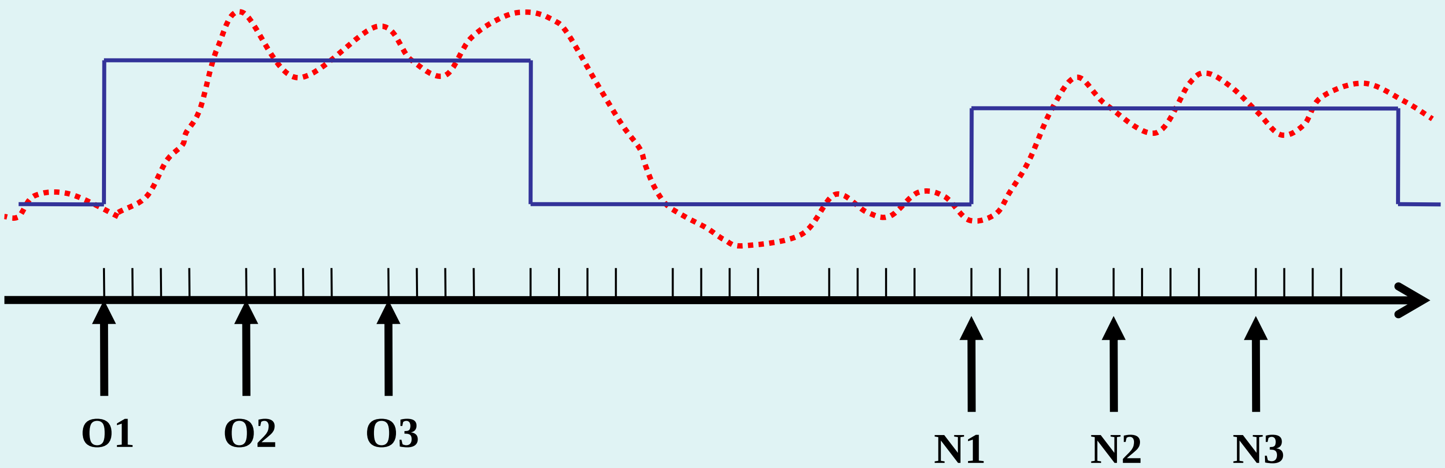
"Oddball"
. . .
Time

Advantages of Event-Related design

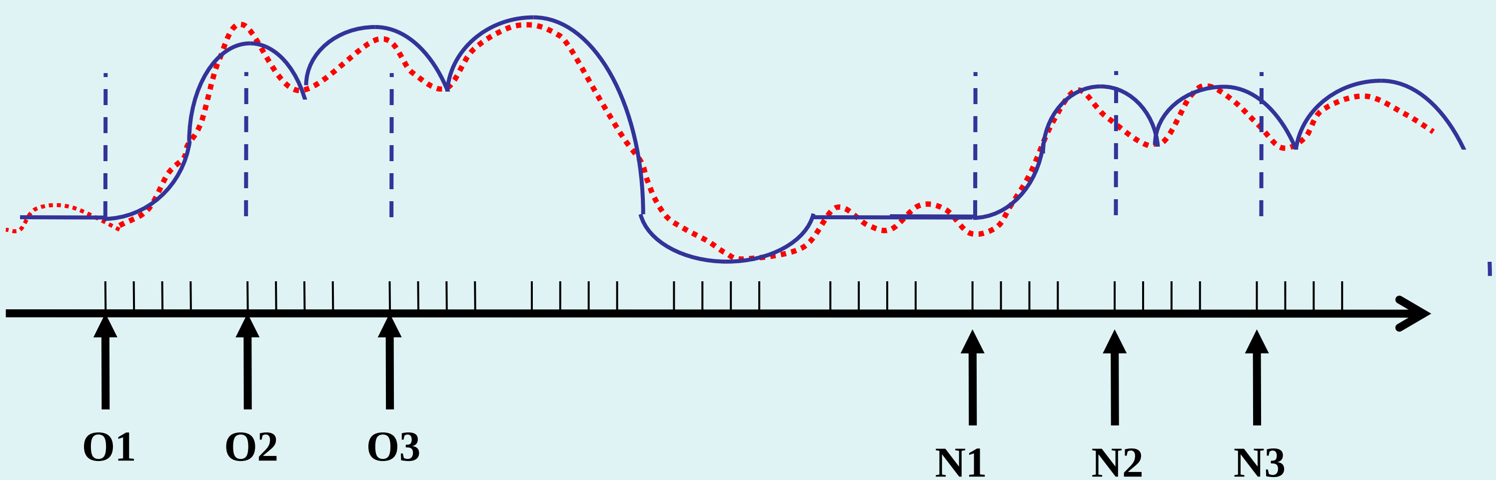
- Randomised trial order
  c.f. confounds of blocked designs
- Post hoc / subjective classification of trials
  e.g, according to subsequent memory
- Some events can only be indicated (in time)
  e.g, spontaneous perceptual changes
- Some trials cannot be blocked
  e.g, "oddball" designs
- More accurate models even for blocked designs?
  e.g, "state-item" interactions

Blocked Design

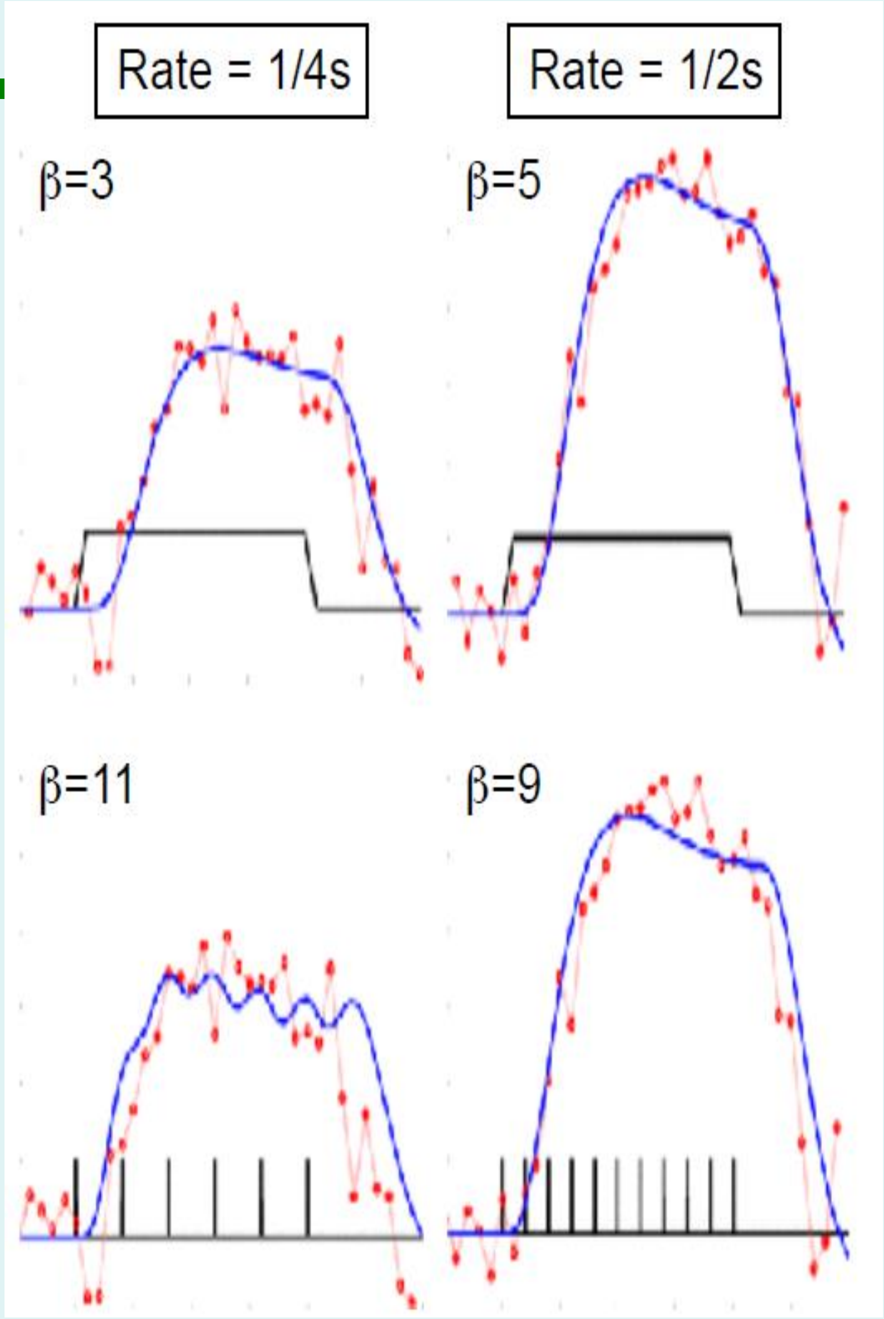
"Epoch" model



"Event" model



- Blocks of trials can be modeled as boxcars or runs of events
- BUT: interpretation of the parameter estimates may differ
- Consider an experiment presenting words at different rates in different blocks:
  - An “epoch” model will estimate parameter **that increases with rate**, because the parameter reflects response per block
  - An “event” model may estimate parameter **that decreases with rate**, because the parameter reflects response per word



Disadvantages of ER designs

- Less efficient for detecting effects than are blocked designs *(see later…)*
- Some psychological processes may be better blocked (e.g. task-switching, attentional instructions)

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- **BOLD impulse response**
- Temporal Basis Functions
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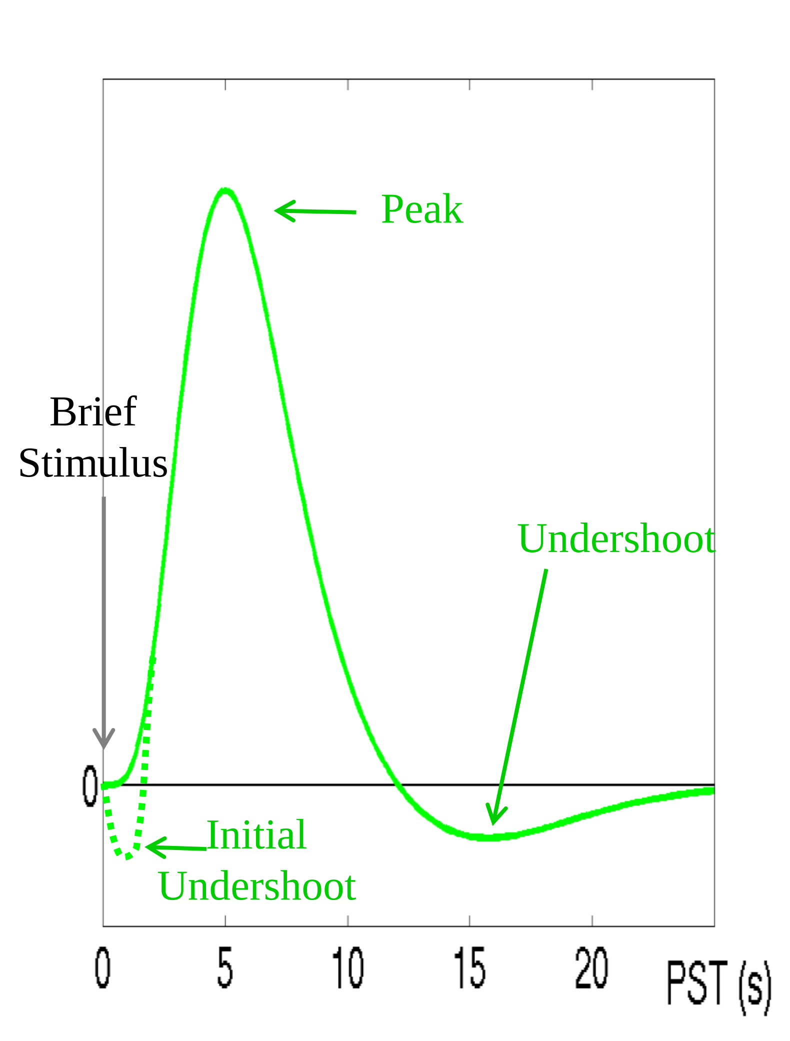
Haemodynamic response function

- Function of blood oxygenation, flow, volume (Buxton et al, 1998)
- Peak (max. oxygenation) 4-6s poststimulus; baseline after 20-30s
- Initial undershoot can be observed (Malonek & Grinvald, 1996)
- Similar across V1, A1, S1…
- … but differences across: other regions (Schacter et al 1997) and individuals (Aguirre et al, 1998)



General Linear (Convolution) Model

GLM for a single voxel:

$$y(t) = u(t) \otimes h(\tau) + \varepsilon(t)$$

$u(t)$ = neural causes (stimulus train)

$$u(t) = \sum \delta(t - nT)$$

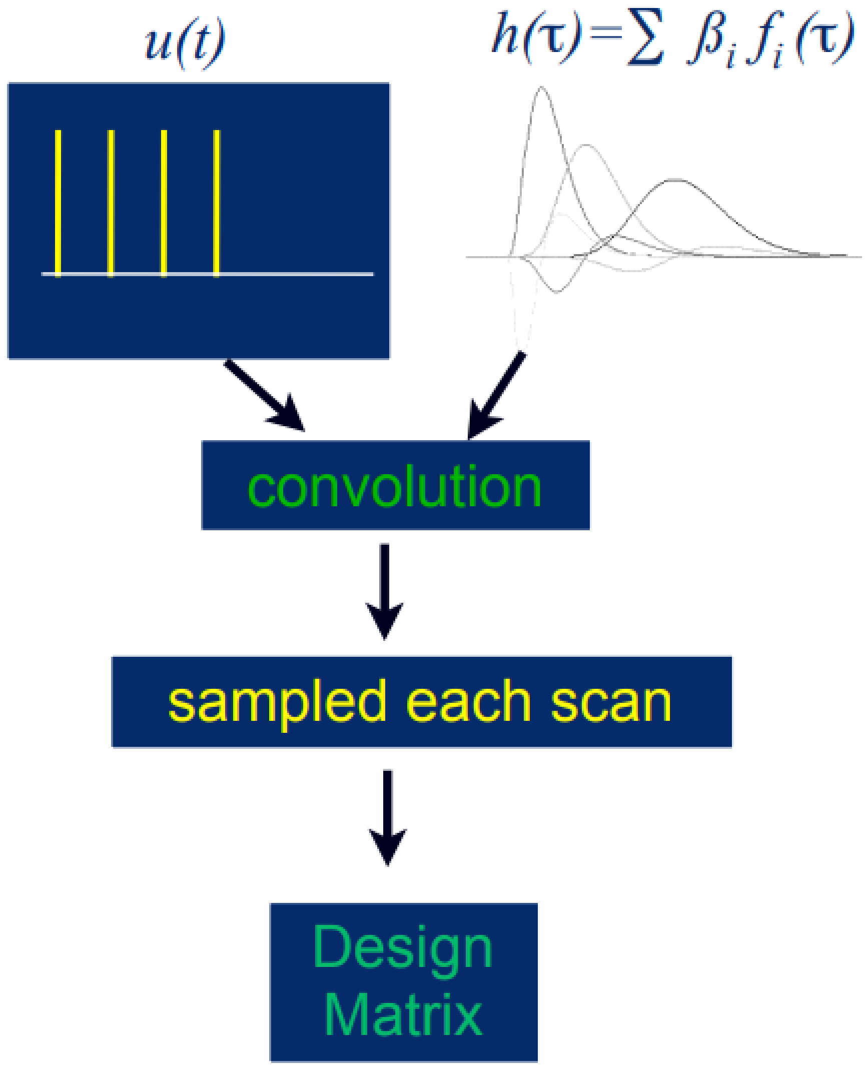
$h(\tau)$ = hemodynamic (BOLD) response

$$h(\tau) = \sum \beta_i f_i(\tau)$$

$f_i(\tau)$ = temporal basis functions

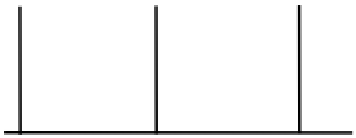
$$y(t) = \sum \sum \beta_i f_i(t - nT) + \varepsilon(t)$$

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}$$

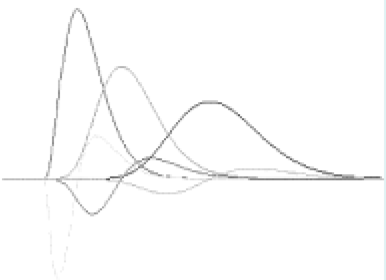


General Linear Model in SPM

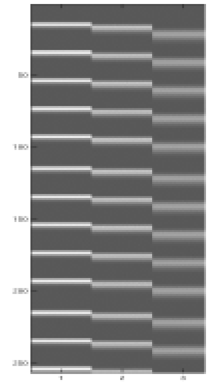
Stimulus
every 20s



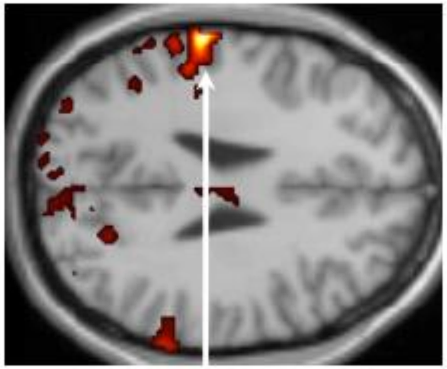
Gamma functions $f_i(\tau)$ of
peristimulus time τ
(Orthogonalised)

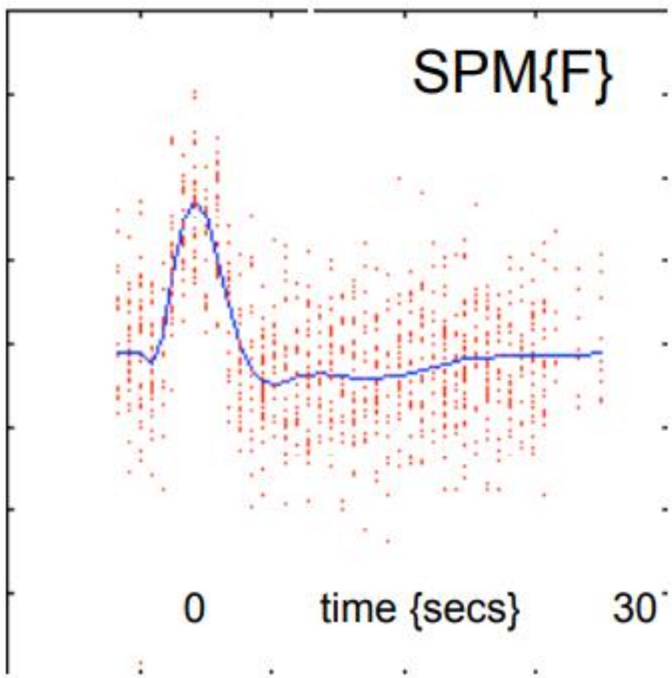


Sampled every TR = 1.7s
Design matrix, $\mathbf{X}$
$[x(t)\otimes f_1(\tau) \mid x(t)\otimes f_2(\tau) \mid \ldots]$



…





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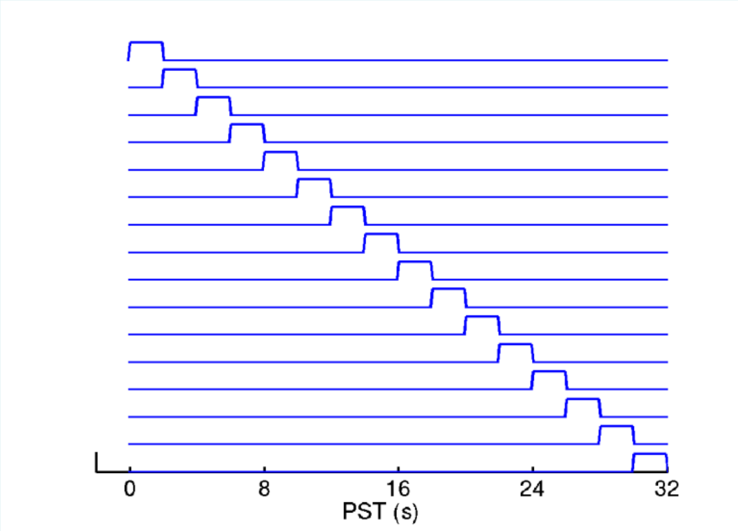
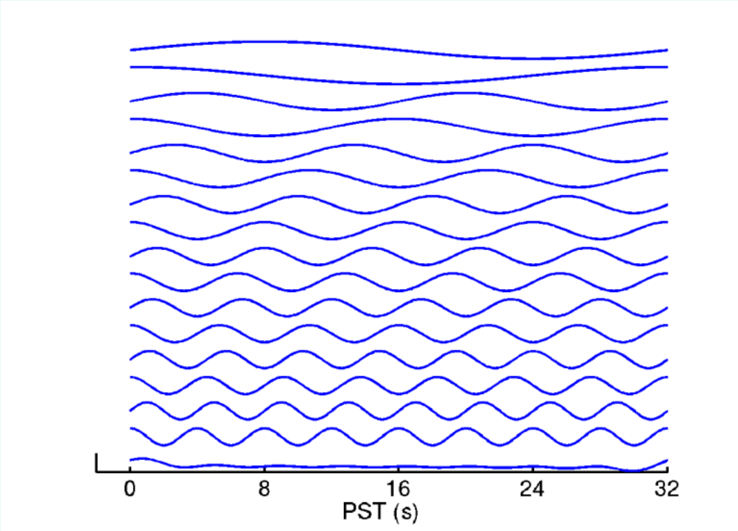
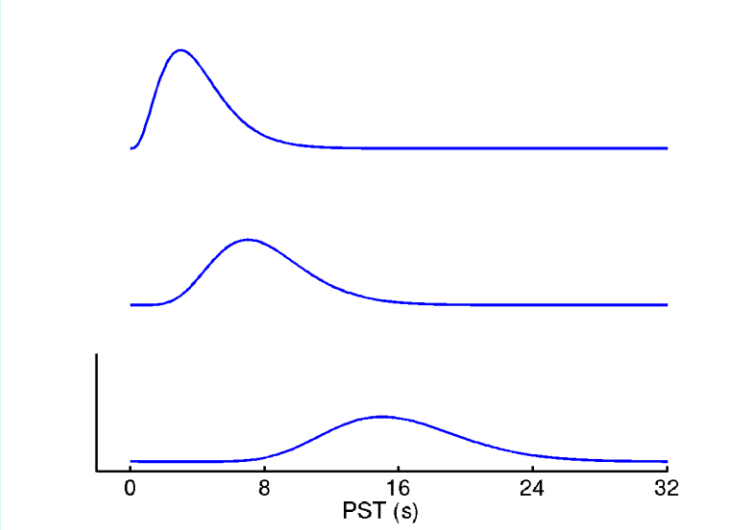
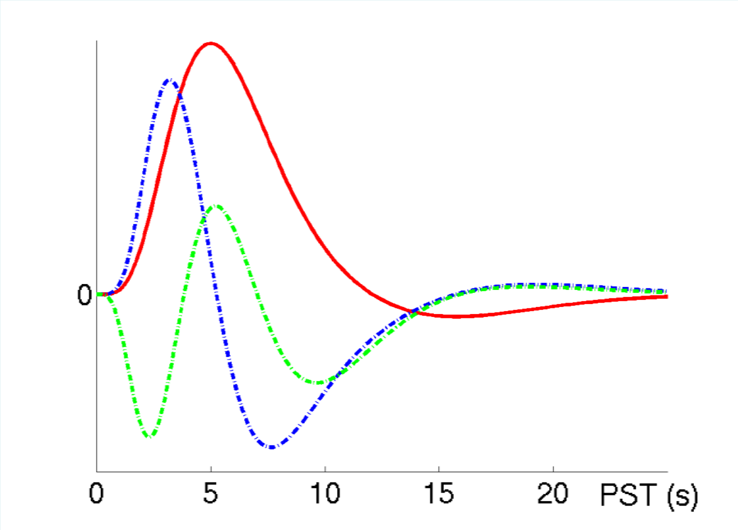
Temporal Basis Functions





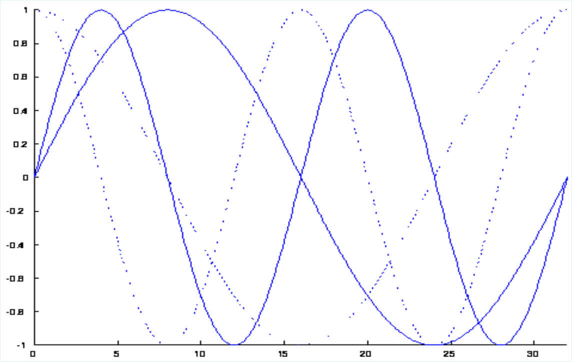




Temporal Basis Functions

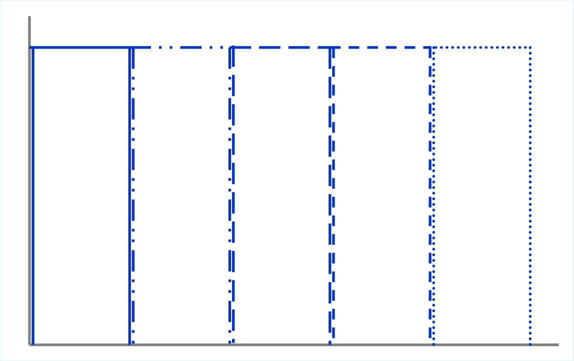
- Fourier Set

  Windowed sines & cosines
  Any shape (up to frequency limit)
  Inference via F-test



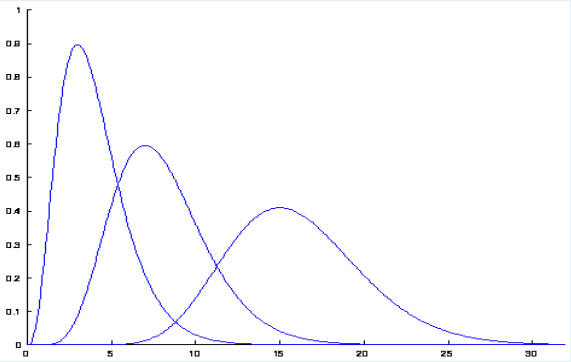
- Finite Impulse Response (FIR)

  Mini timebins (selective averaging)
  Any shape (up to bin-width)
  Inference via F-test



Temporal Basis Functions

- Gamma Functions
  - Bounded, asymmetrical (like BOLD)
  - Set of different lags
  - Inference via F-test



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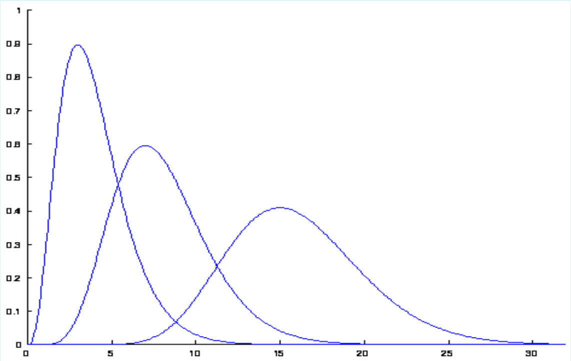
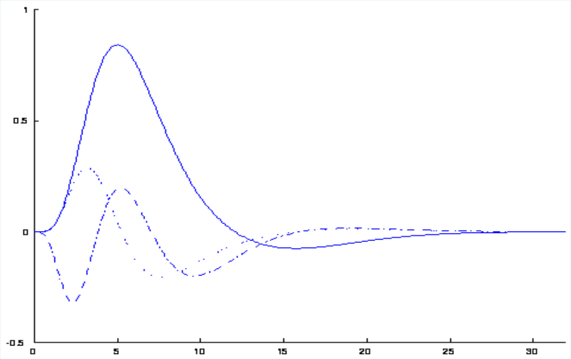
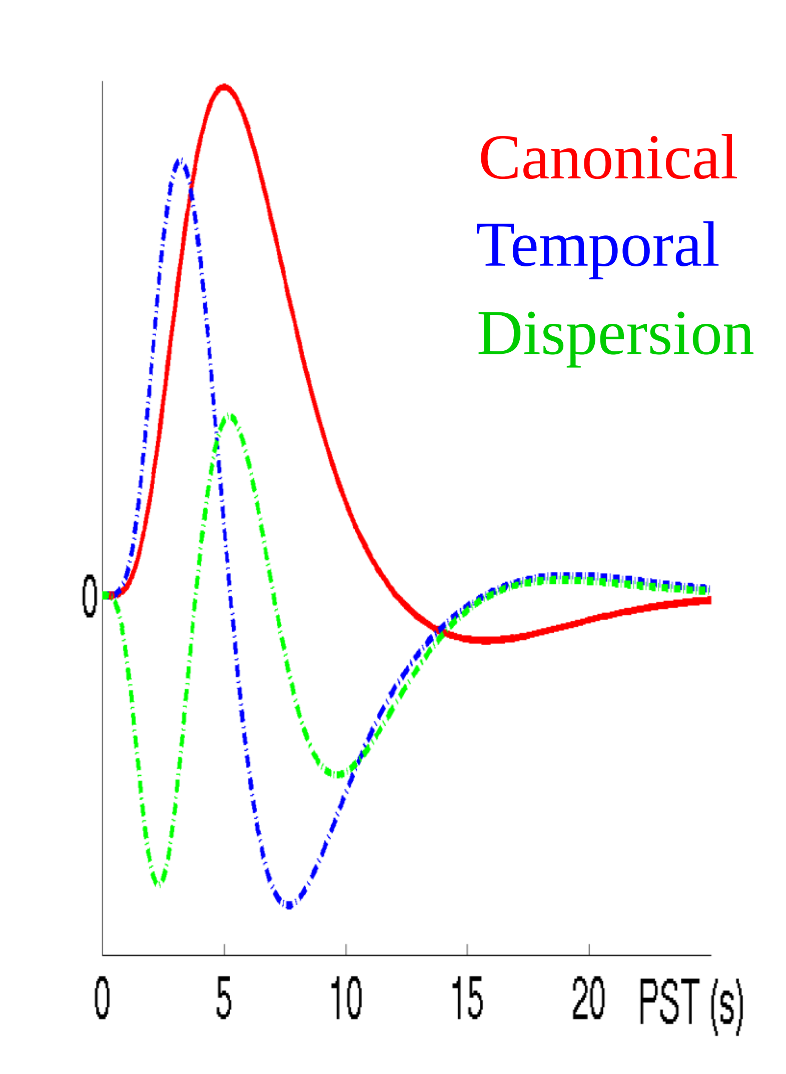


- Informed Basis Set

  Best guess of canonical BOLD response
  Variability captured by Taylor expansion
  "Magnitude" inferences via
  t-test…?



Temporal Basis Functions



- Informed Basis Set

  (Friston et al. 1998)

- Canonical HRF (2 gamma functions)

  plus Multivariate Taylor expansion in:

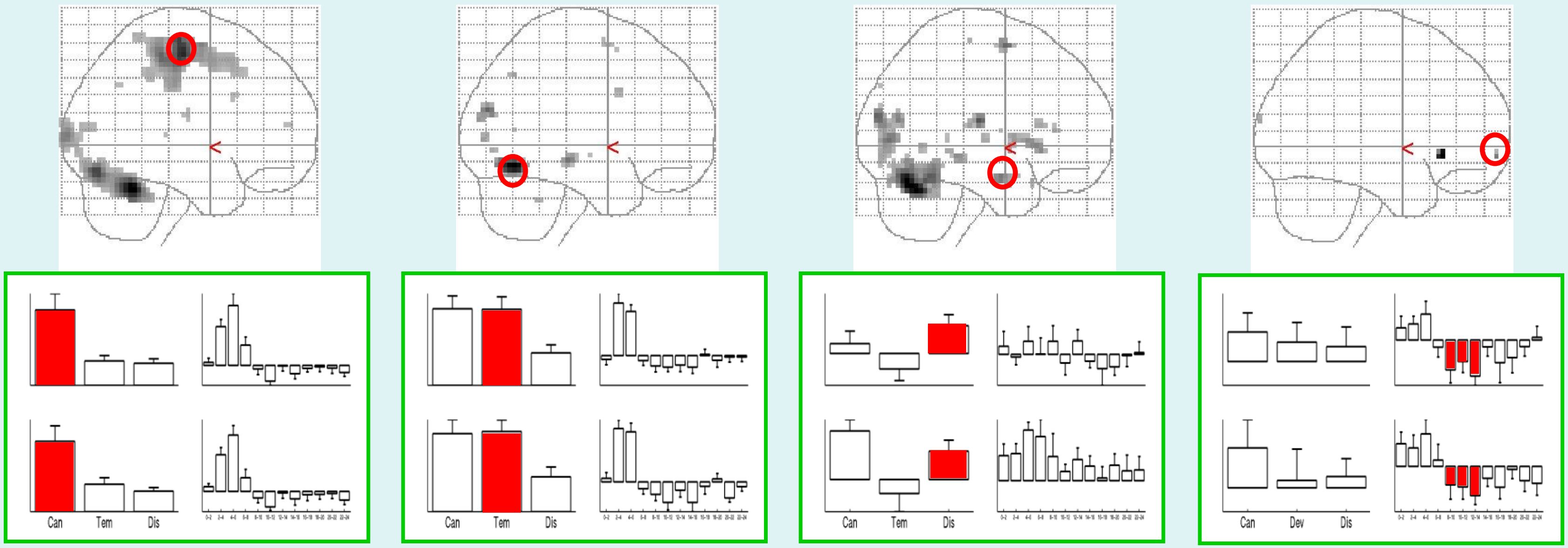
  time (*Temporal Derivative*)

  width *(Dispersion Derivative)*

- "Magnitude" inferences via t-test on canonical parameters (providing canonical is a good fit…more later)
- "Latency" inferences via tests on *ratio* of derivative : canonical parameters (more later…)

Temporal Basis Functions, which one(s)?

In this example (rapid motor response to faces, *Henson et al, 2001*)…



Canonical + Temporal + Dispersion + FIR

…canonical + temporal + dispersion derivatives appear sufficient

…may not be for more complex trials (eg stimulus-delay-response)

…but then such trials better modelled with separate neural components (ie activity no longer delta function) + constrained HRF (Zarahn, 1999)

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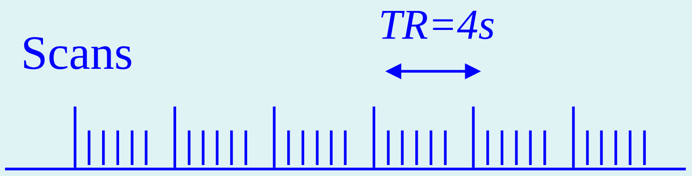
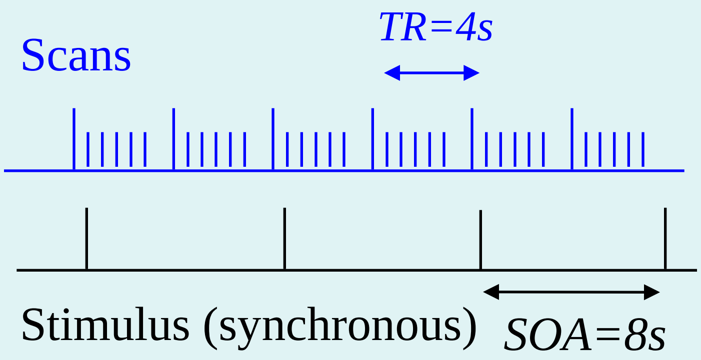
Timing Issues

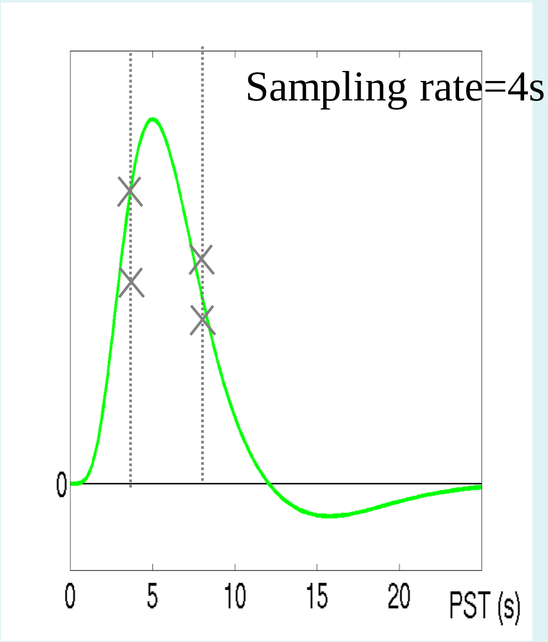
- Typical TR for 48 slice EPI at 3mm spacing is ~ 4s



Timing Issues

- Typical TR for 48 slice EPI at 3mm spacing is ~ 4s
- Sampling at [0,4,8,12…] post- stimulus may miss peak signal





Timing Issues

- Typical TR for 48 slice EPI at 3mm spacing is ~ 4s
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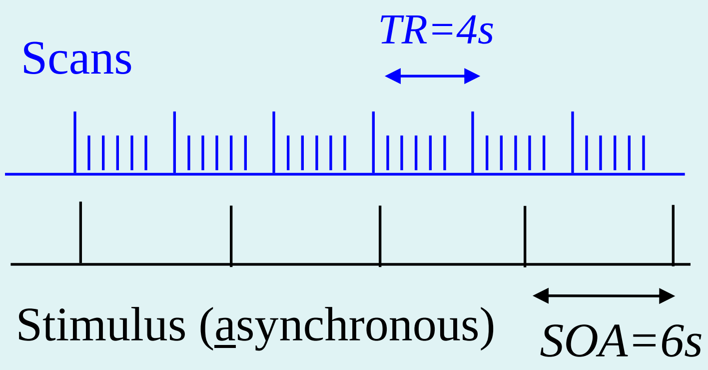
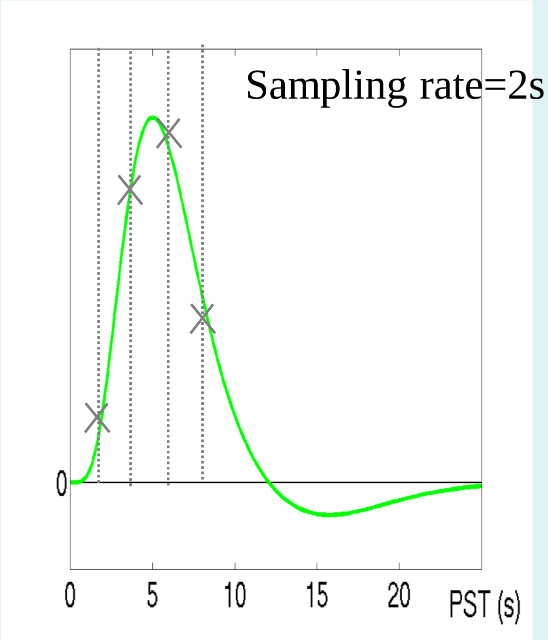
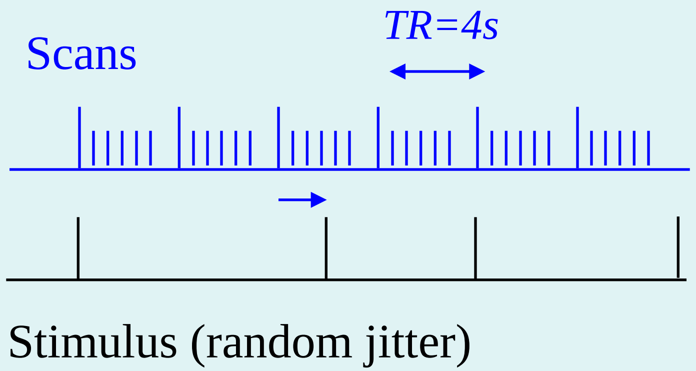
- Higher effective sampling by:
  1. Asynchrony, *e.g. SOA=1.5TR*

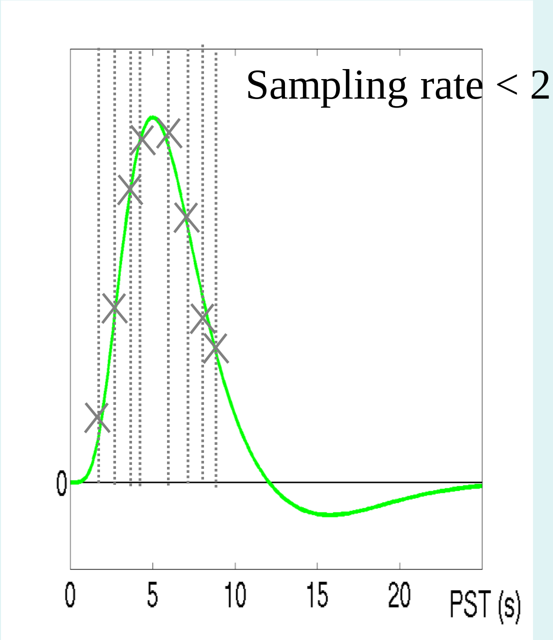




Timing Issues

- Typical TR for 48 slice EPI at 3mm spacing is ~ 4s
- Sampling at [0,4,8,12…] post- stimulus may miss peak signal
- Higher effective sampling by:
  1. Asynchrony, *e.g. SOA=1.5TR*
  2. Random Jitter, e.g. *SOA=(2±0.5)TR*





BOLD Response Latency (Linear)

- Assume the real response, $r(t)$, is a scaled (by α) version of the canonical, $f(t)$, but delayed by a small amount dt:

$$r(t) = \alpha f(t+dt) \sim \alpha f(t) + \alpha f'(t)\, dt \qquad \textit{1st-order Taylor}$$

- If the fitted response, $R(t)$, is modelled by the canonical + temporal derivative:

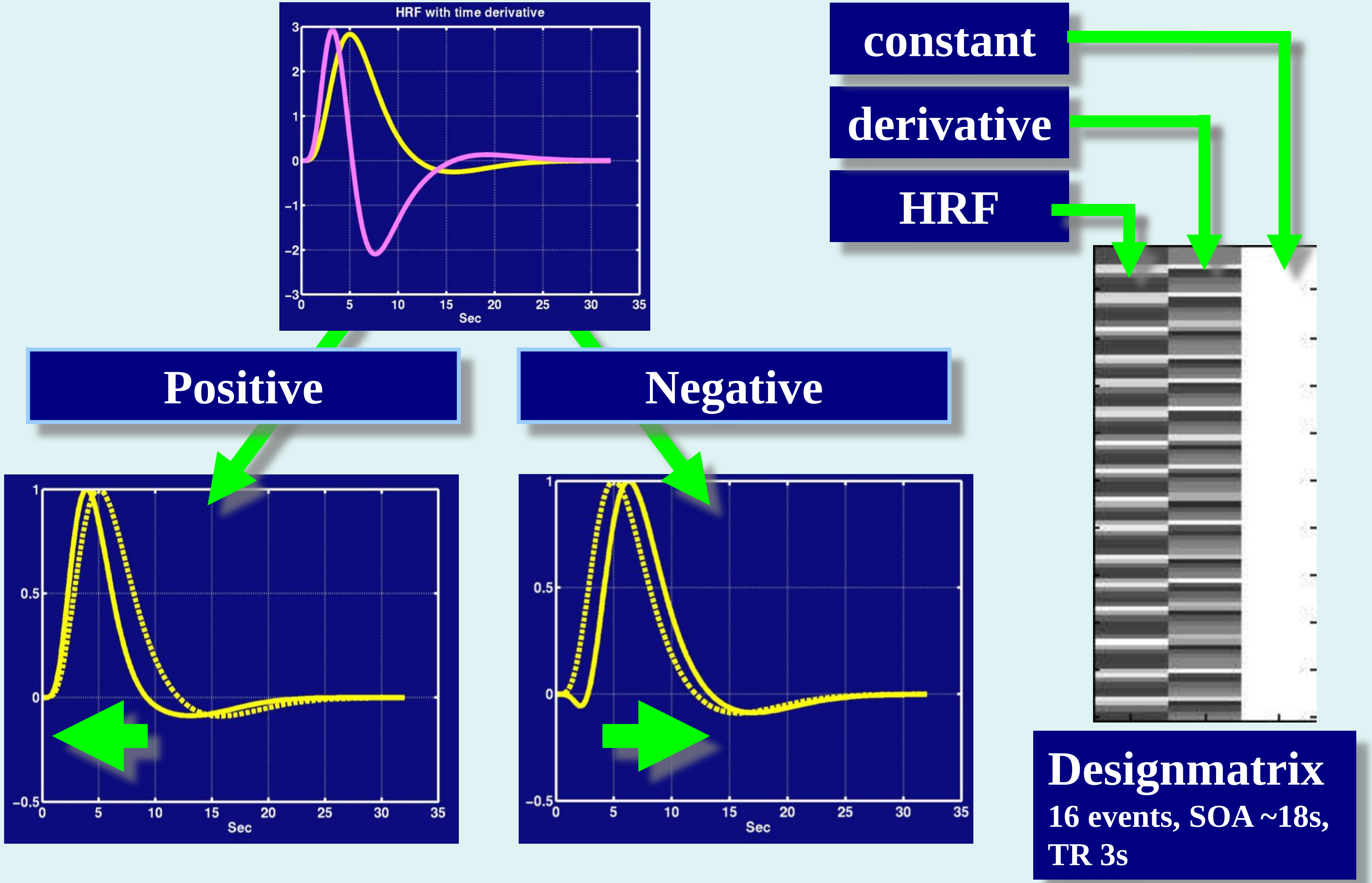
$$R(t) = ß_1 f(t) + ß_2 f'(t) \qquad \textit{GLM fit}$$

- Then canonical and derivative parameter estimates, $ß_1$ and $ß_2$, are such that:

$$\alpha = ß_1 , \quad dt = ß_2 / ß_1$$

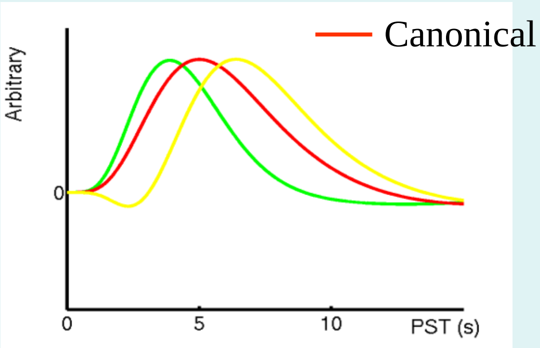
- *i.e. latency can be approximated by the ratio of derivative-to-canonical parameter estimates (within limits of first-order approximation, +/- 1s)*

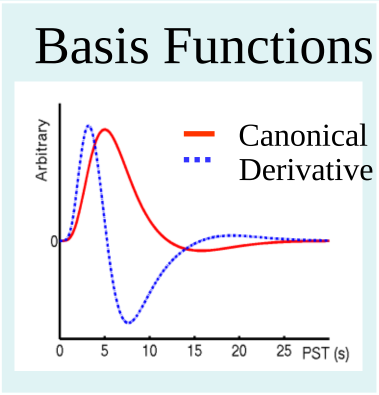
BOLD Response Latency: example

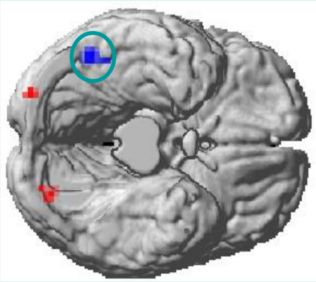


BOLD Response Latency (Linear)

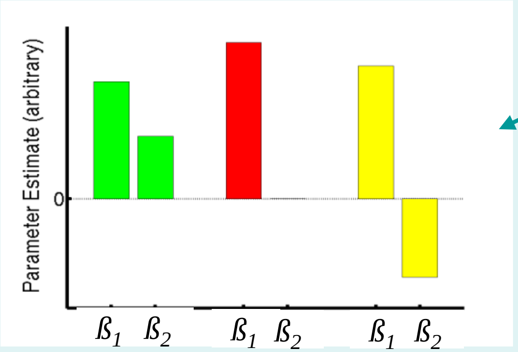
Delayed Responses (green/yellow)

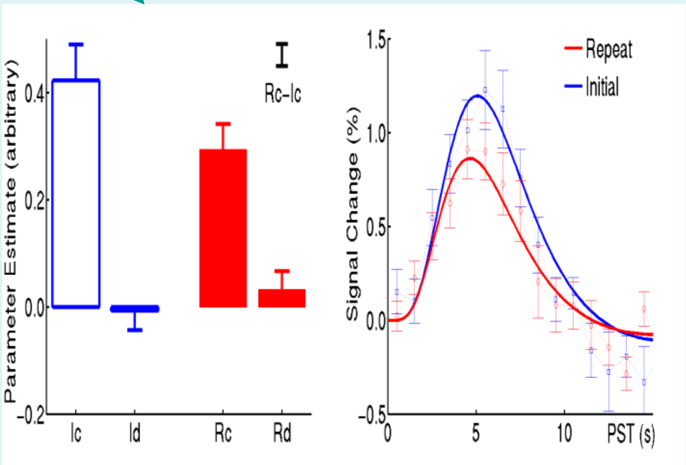




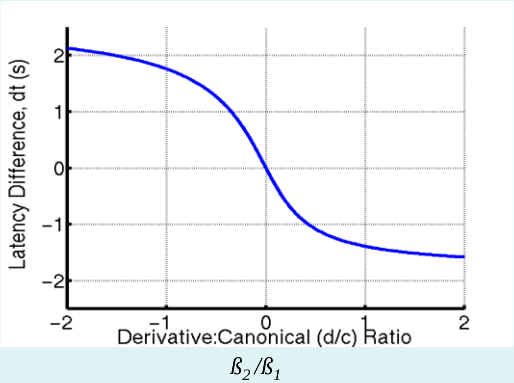


Parameter Estimates





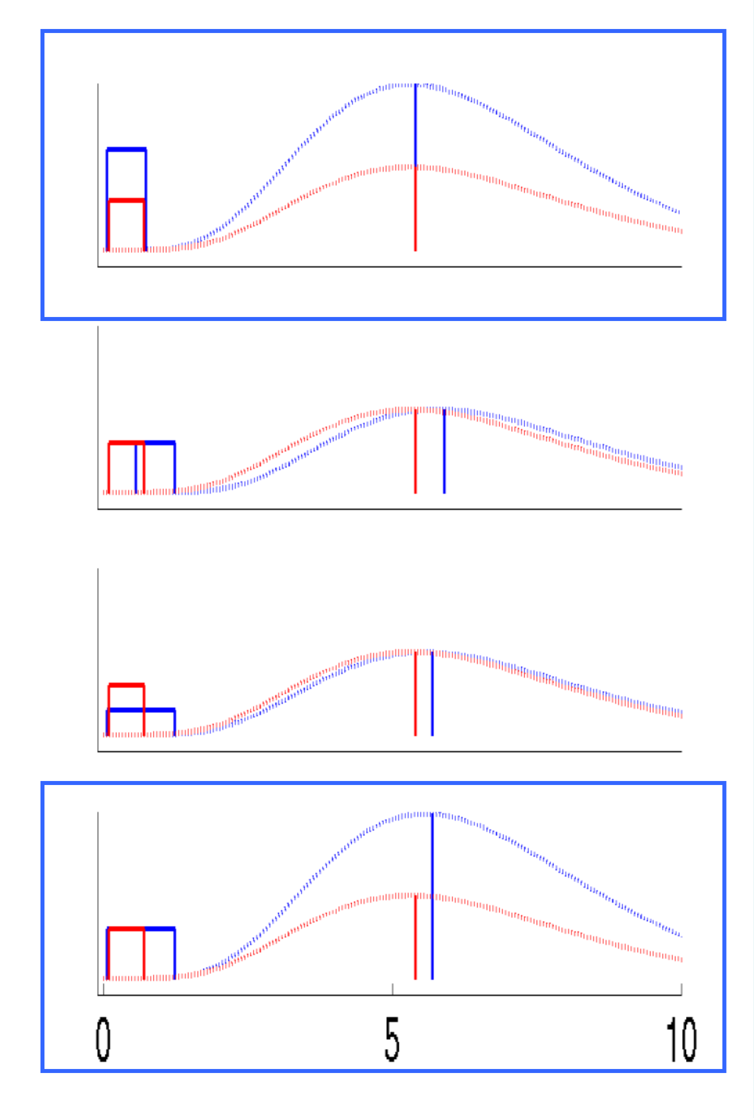
Actual latency, *dt*, vs. $ß_2 / ß_1$



Face repetition reduces latency as well as magnitude of fusiform response

Neural Response Latency

Neural		*BOLD*
A. Decreased		A. Smaller Peak
B. Advanced		B. Earlier Onset
C. Shortened (same integrated)		C. Earlier Peak
D. Shortened (same maximum)		D. Smaller Peak *and earlier Peak*



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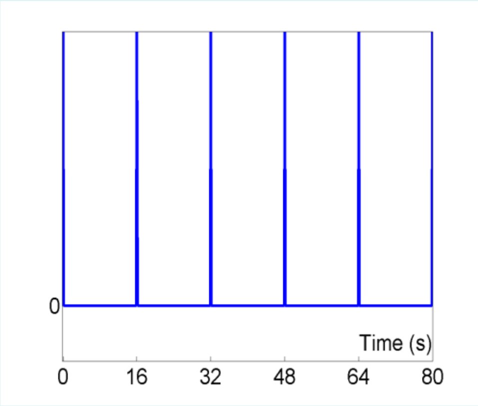
Fixed SOA = 16s

Stimulus (“Neural”)



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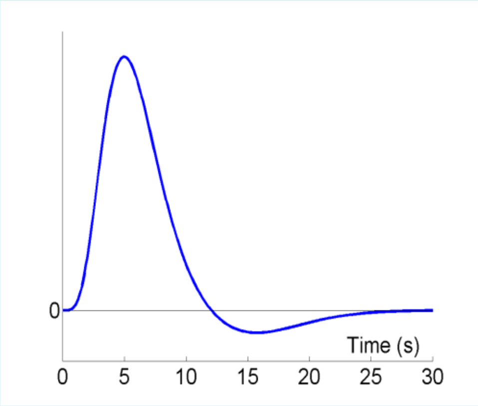
HRF



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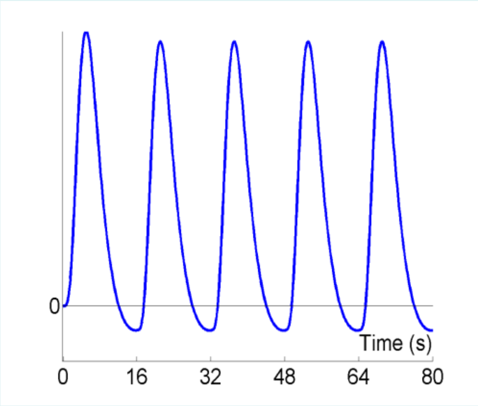
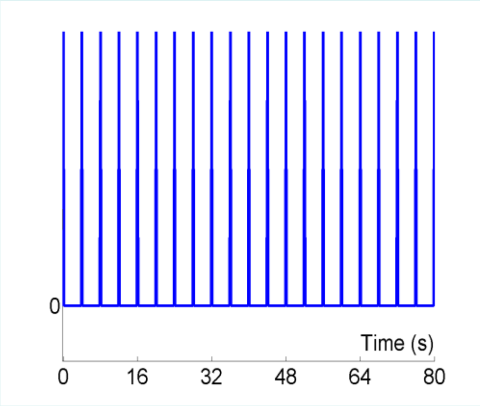
Predicted Data



Not particularly efficient…

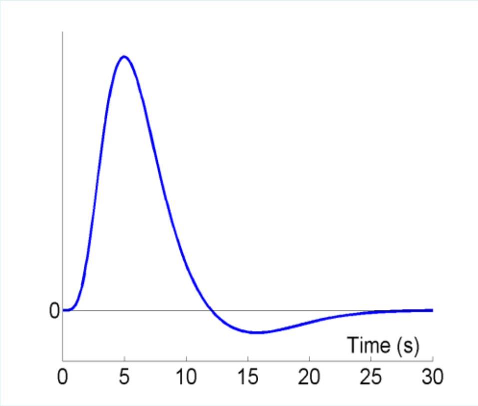
Fixed SOA = 4s

Stimulus (“Neural”)



⊗

HRF



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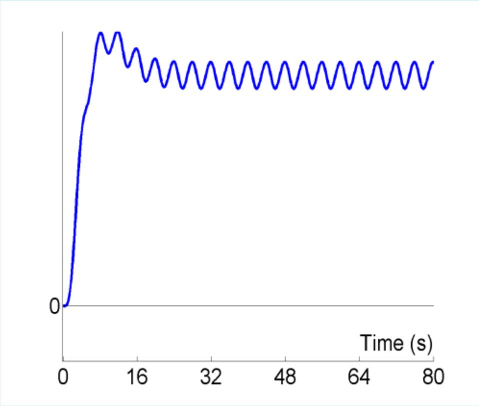
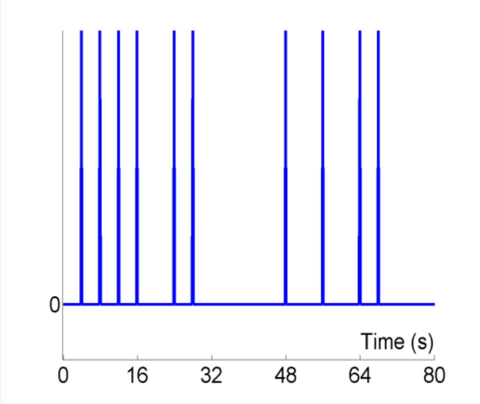
Predicted Data



Very Inefficient…

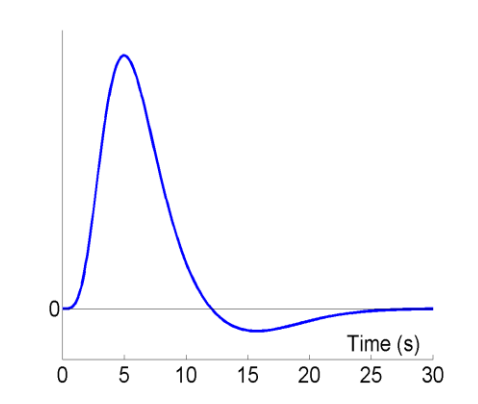
Randomised, SOA_{min}= 4s

Stimulus ("Neural")



$\otimes$

HRF



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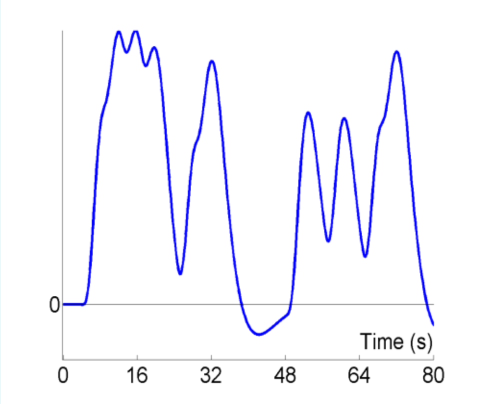
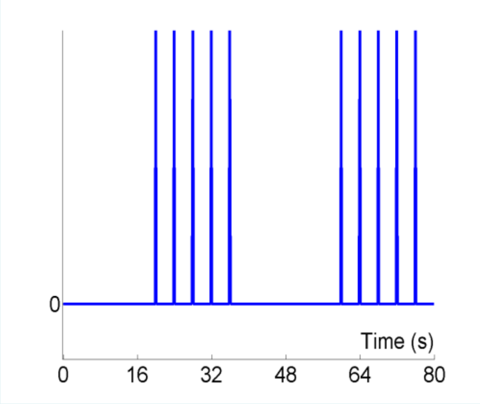
Predicted Data



More Efficient…

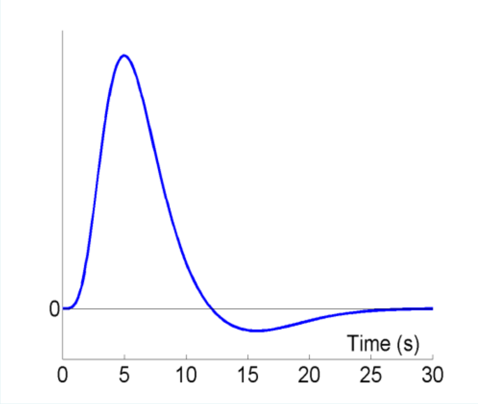
Blocked, SOA_{min}= 4s

Stimulus ("Neural")



$\otimes$

HRF



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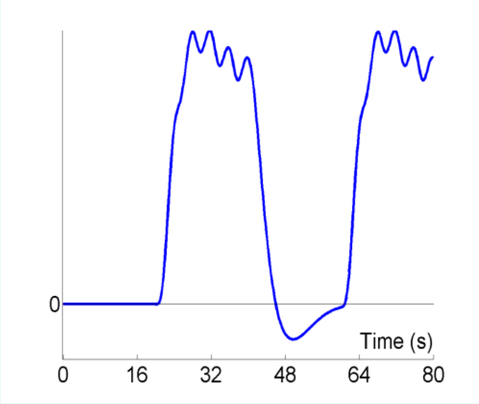
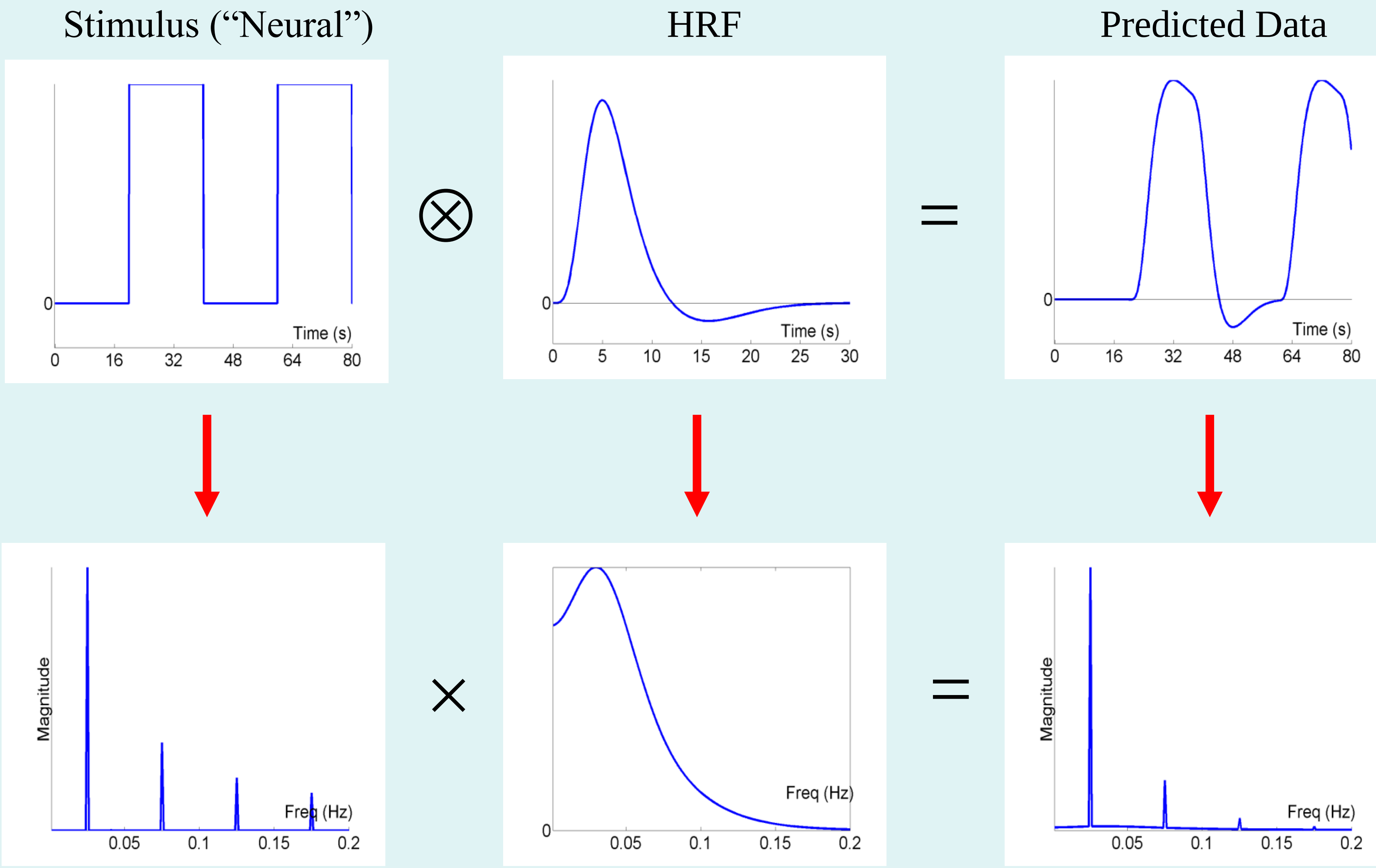
Predicted Data



Even more Efficient…

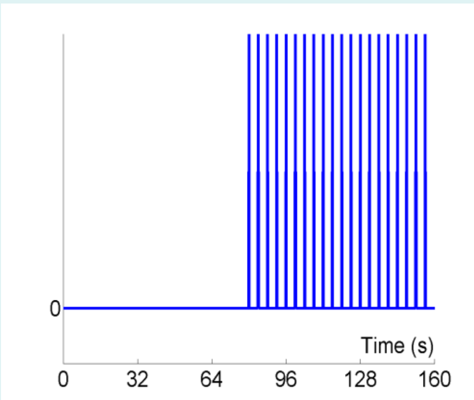
Blocked, epoch = 20s



Blocked-epoch (with small SOA) and Time-Freq equivalences

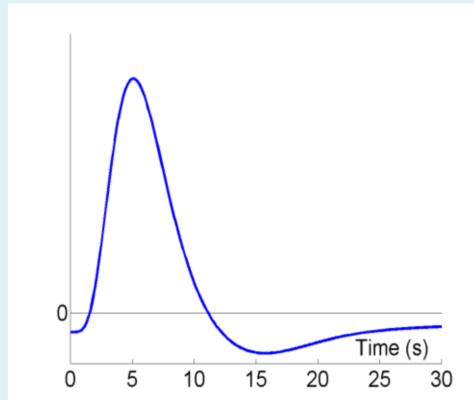
Blocked (80s), SOA_{min}=4s, highpass filter = 1/120s

Stimulus (“Neural”)



⊗

HRF



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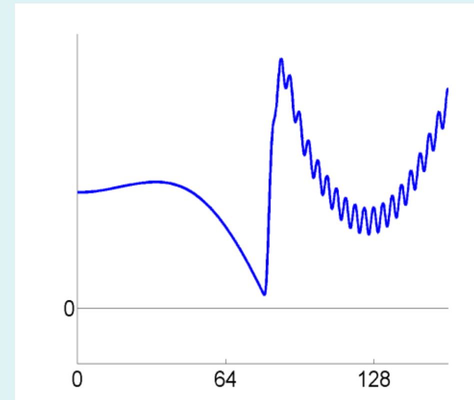
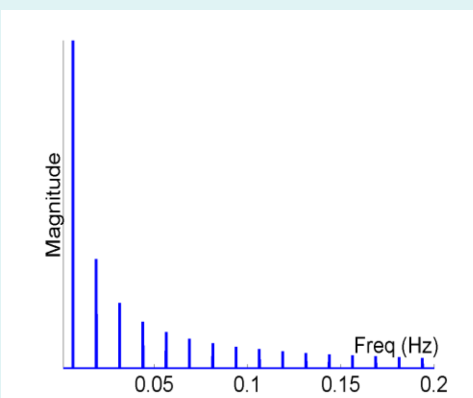
Predicted Data



“Effective HRF” (after highpass filtering)
(Josephs & Henson, 1999)



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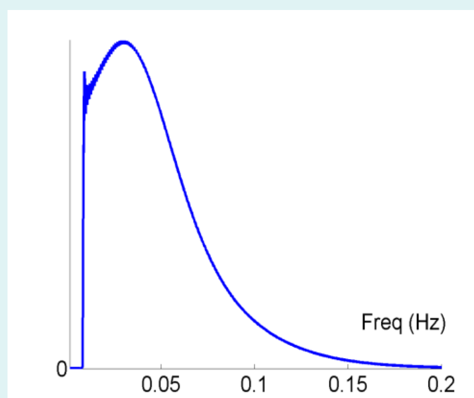

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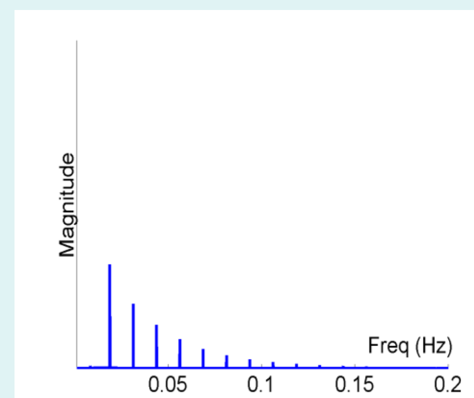
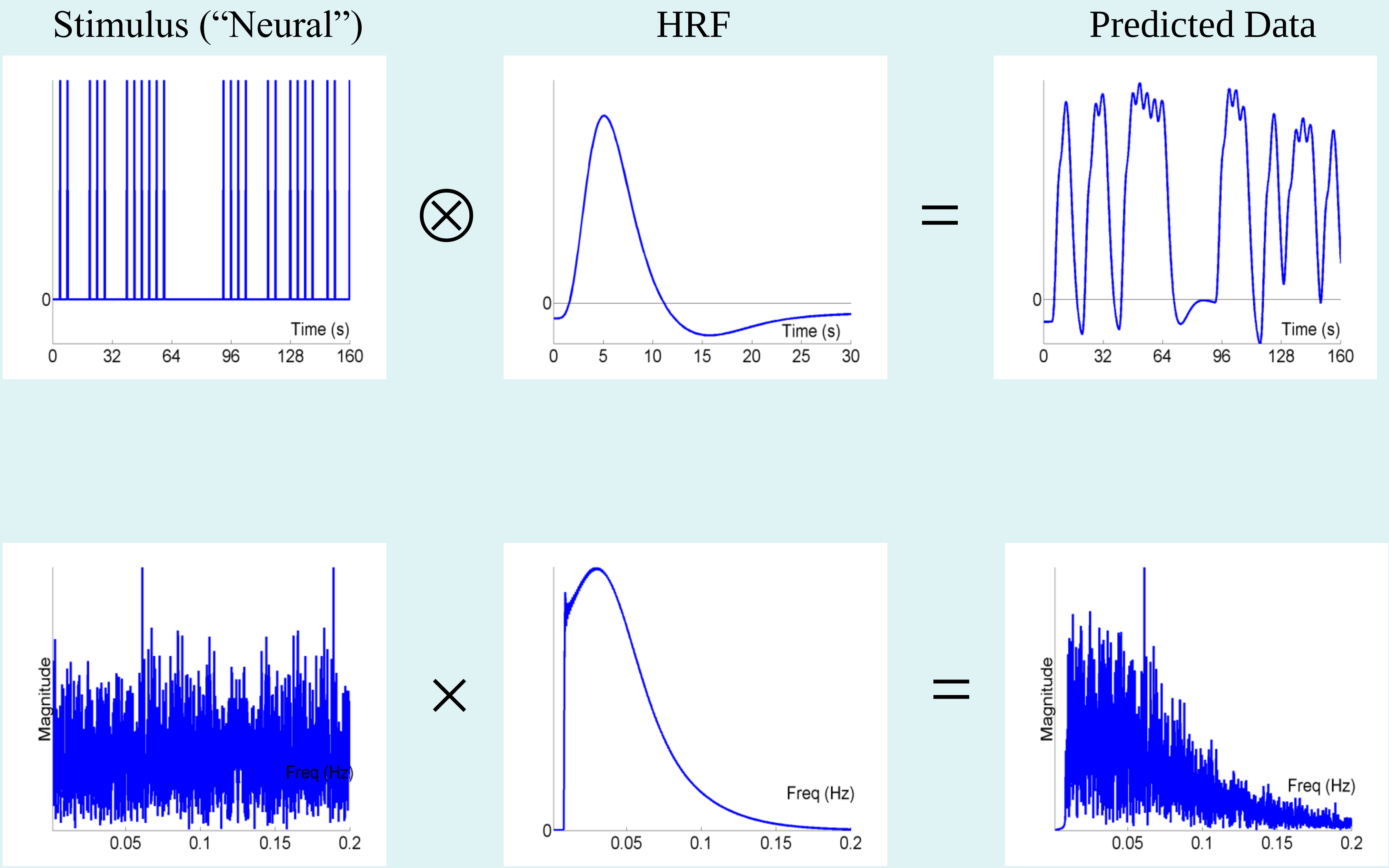


Don’t have long (>60s) blocks!

Randomised, SOA_{min}=4s, highpass filter = 1/120s



(Randomised design spreads power over frequencies)

Design Efficiency

Maximise efficiency by maximising t, by minimising the squared variance:

$$t = \frac{c^T \beta}{\sqrt{\mathrm{var}(c^T \beta)}}$$

X: design matrix
c: contrast vector
β: beta vector

Assuming that the error in our model is 'iid', each observation is drawn independently from a Gaussian distribution:

$$b \sim N(b, s^2 (X^T X)^{-1})$$

$$\mathrm{var}(c^T b) = s^2 c^T (X^T X)^{-1} c$$

Assuming σ is independent of our design, taking a fixed contrast we can only alter our design matrix to improve efficiency.

Formal definition of **design efficiency** minimises variance:

$$e \gg \frac{1}{\sqrt{c^T (X^T X)^{-1} c}}$$

Given the contrast of interest, **minimise covariance in the design matrix**

Efficiency can be estimated before using the design

Design efficiency: Trial sequencing

- Design parametrised by:

  SOA_{min} Minimum SOA

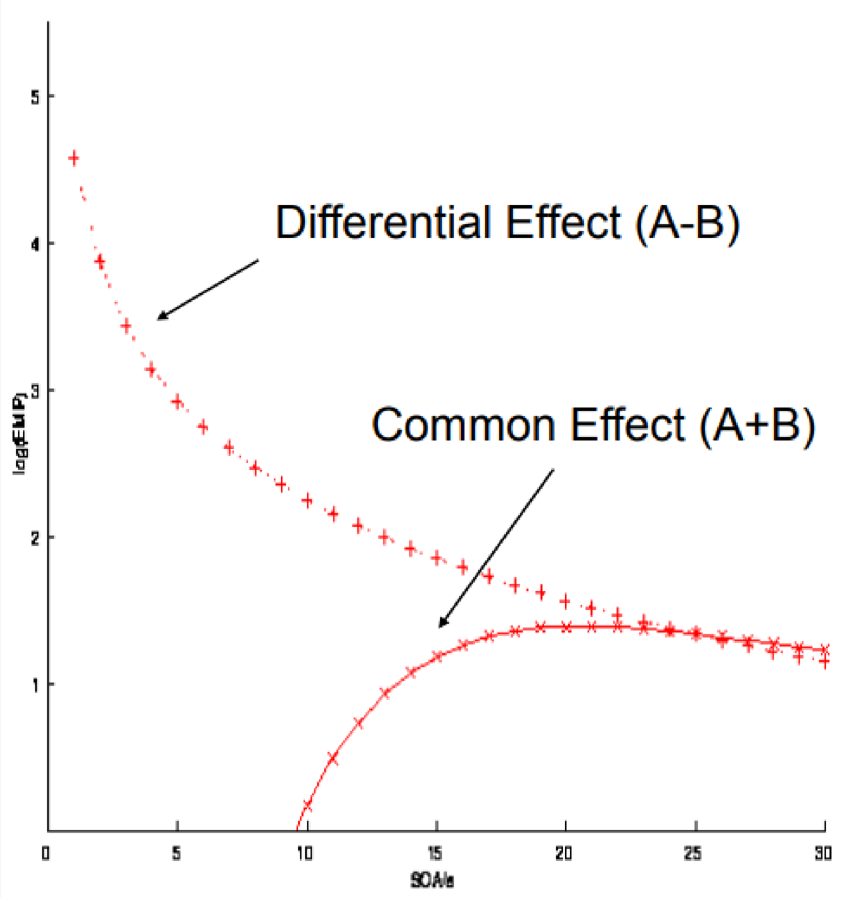
  $p_i(\mathbf{h})$ Probability of event-type *i* given history ***h*** of last *m* events

- With *n* event-types $p_i(\mathbf{h})$ is a *n x n Transition Matrix*

- Example: Randomised AB

	A	**B**
A	0.5	0.5
B	0.5	0.5

=> ABBBABAABABAAA...



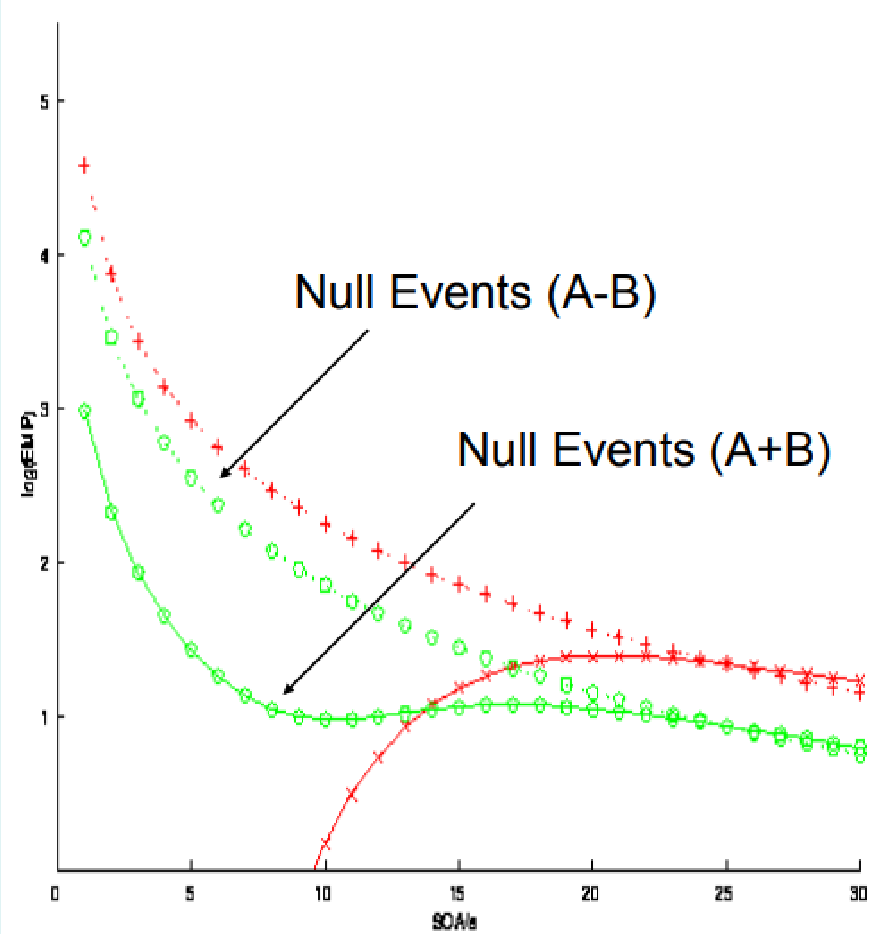
Design efficiency: Trial sequencing

- Example: Null events

	A	B
A	0.33	0.33
B	0.33	0.33

  => AB-BAA--B---ABB...

- Efficient for differential and main effects at short SOA
- Equivalent to stochastic SOA (Null Event like third unmodelled event-type)



Design efficiency: Trial sequencing

- Example: Alternating AB

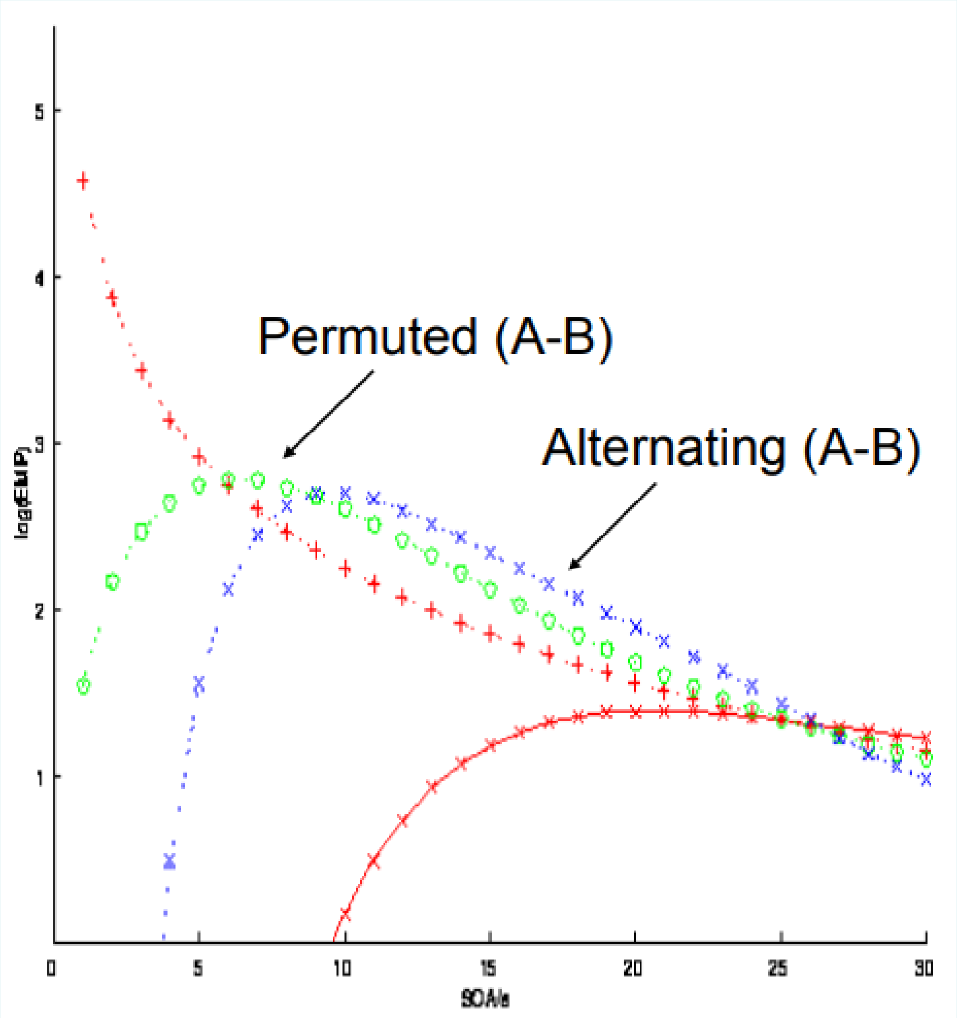
	A	B
A	0	1
B	1	0

=> ABABABABABAB...

- Example: Permuted AB

	A	B
AA	0	1
AB	0.5	0.5
BA	0.5	0.5
BB	1	0

=> ABBAABABABBA...



Design efficiency: Conclusions

- Optimal design for one contrast may not be optimal for another
- Blocked designs generally most efficient (with short SOAs, given optimal block length is not exceeded)
- However, psychological efficiency often dictates intermixed designs, and often also sets limits on SOAs
- With randomised designs, optimal SOA for differential effect (A-B) is minimal SOA (>2 seconds, and assuming no saturation), whereas optimal SOA for main effect (A+B) is 16-20s

Design efficiency: Conclusions

- Inclusion of null events improves efficiency for main effect at short SOAs (at cost of efficiency for differential effects)
- If order constrained, intermediate SOAs (5-20s) can be optimal
- If SOA constrained, pseudorandomised designs can be optimal (but may introduce context-sensitivity)