TEST OF GOODNESS OF POPULATION RECEPTIVE FIELD ESTIMATES

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INTRODUCTION

We present a method based on computer simulations to test the goodness of population receptive field (pRF) estimates. In particular, we have examined the effect of having non-linearity in the hemodynamic response function (HRF) by,

1. Simulating fMRI responses with non-linear "simulation HRFs"
2. Estimating pRFs with a "similar" linear "estimation HRF"

This is an important scenario to test since many estimation methods assume linear HRF models but actual HRF response is non-linear. Hence we present a pipeline to test robustness of stimulation protocols against non-linearities in the BOLD response.

METHOD

We have developed a test based on models in [1][2] with following steps:

1. Parameter Initialization

Define pRF vector $\Theta = (x_0, y_0, \sigma)$.
Initialize $\Theta = \theta$ such that x_0, y_0 are receptive field locations in the visual field corresponding to a voxel measurement and the pRF size is modeled accordingly to account for cortical mapping,

$$\sigma = \frac{1}{2}\ln(e + \sqrt{x_0^2 + 2y_0^2})$$

2. Data Generation

$$g(x, y, \Theta = \theta) = e^{-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}}$$

$$r(t, \Theta = \theta) = (\sum_{x,y} s(x, y, t)g(x, y, \theta))^n$$

$$B(t) = h(r(t, \Theta = \theta)) + e(t)$$

3. Parameter Estimation

$$r(t, \Theta) = (\sum_{x,y} s(x, y, t)g(x, y, \Theta))^n$$

$$p(t, \Theta) = h(r(t, \Theta))$$

$$\hat{\Theta} = \arg\min \sum_t (B(t) - p(t, \Theta))^2$$

4. Accuracy Map Evaluation

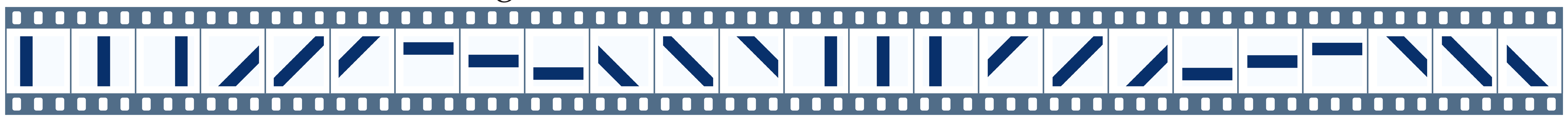
$$\tilde{x} = \frac{|\hat{x_0} - x_0|}{x_0},\ \tilde{y} = \frac{|\hat{y_0} - y_0|}{y_0},\ \tilde{\sigma} = \frac{|\hat{\sigma} - \sigma|}{\sigma}$$

with following variable descriptions:

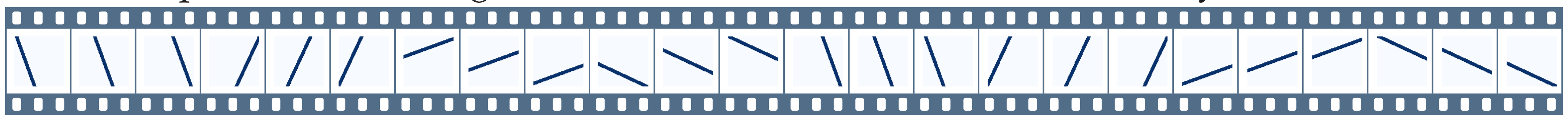
$$\begin{aligned} x, y &= \text{point in visual space} \\ n &= \text{spatial linearity factor} \\ g(x, y, \Theta) &= \text{pRF model} \\ s(x, y, t) &= \text{stimulation function} \\ r(t, \Theta) &= \text{pRF response} \\ e(t) &= \text{Gaussian noise} \\ B(t) &= \text{BOLD response} \\ h(.) &= \text{HRF function} \end{aligned}$$

STIMULATION

We first used the exact drifting bar stimululation in [1]:



Then we optimized it for angle and bar width to reduce the non-linearity:



EXPERIMENT

We use following HRFs:

- Double-Gamma Linear HRF

$$p(t) = r(t) * h(t)$$

$$h(t) = \frac{1}{C}\frac{\lambda_1^{n_1}(t-t_1)^{n_1-1}e^{-\lambda_1(t-t_1)}}{(n_1-1)!} - a\frac{\lambda_2^{n_2}(t-t_2)^{n_2-1}e^{-\lambda_2(t-t_2)}}{(n_2-1)!}$$

where C is the normalizing constant.

- Friston Non-Linear HRF

$$p(t) = \sum_{i=1}^{3}\beta_i x_i(t) + \sum_{i=1}^{3}\sum_{j=1}^{3}\beta_{ij}x_i(t)x_j(t)$$

$$x_i(t) = (r * b_i)(t)$$

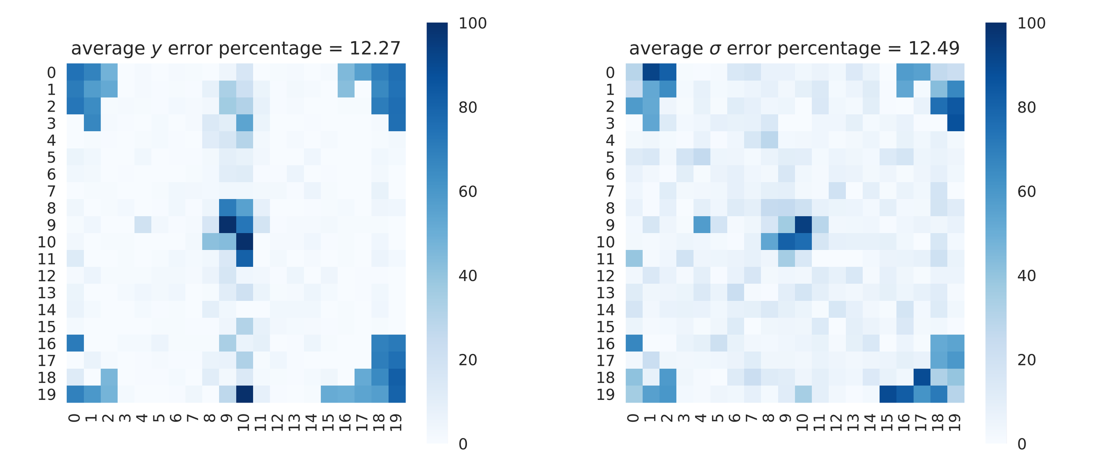
$$b_i(t) = \frac{1}{k!}t^k e^{-t} \quad k = 5, 7, 15$$

HRF non-linearity experiment steps:

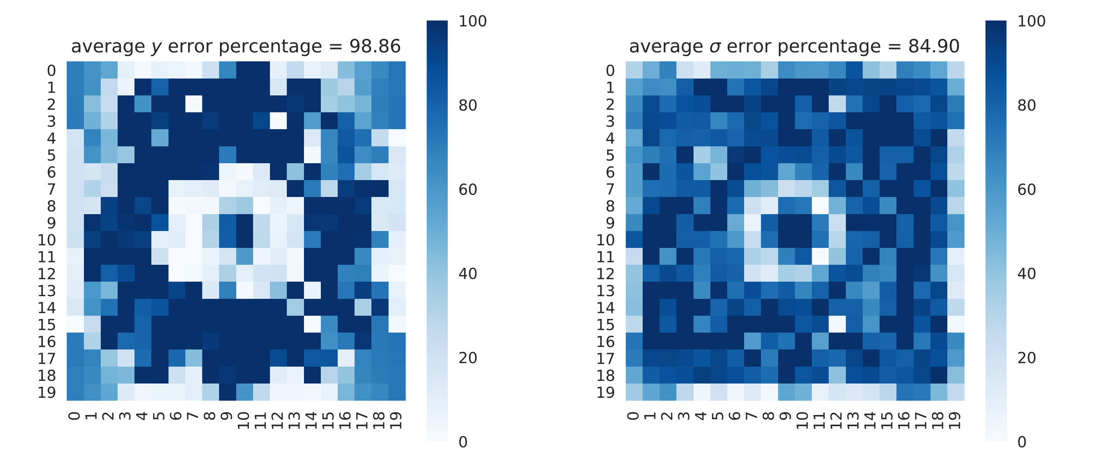
1. Initialize parameters
   (a) number of voxels to simulate
   (b) spatial linearity factor
   (c) double-Gamma HRF
   (d) Friston non-Linear HRF
2. Generate BOLD with non-linear HRF
3. Estimate with linear HRF
4. Repeat 3 to optimize the bar width size
5. Repeat 3 with optimized bar width to optimize the rotation angle

RESULTS

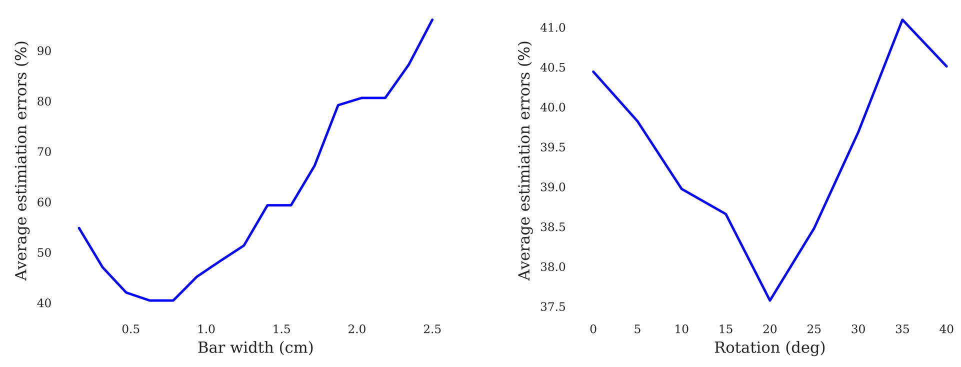
Accuracy maps when simulating with non-linear HRF and estimating with non-linear HRF.



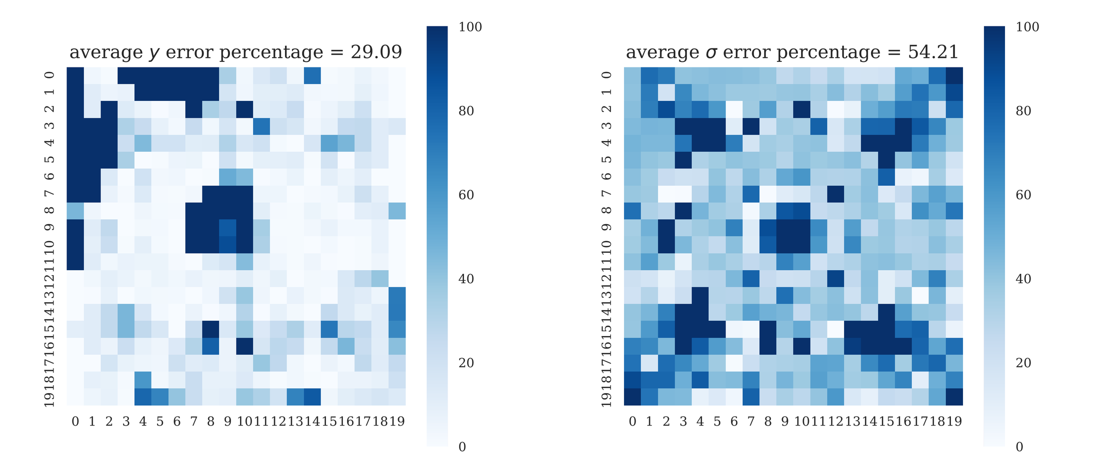
Accuracy maps when simulating with non-linear HRF and estimating with linear HRF:



Optimization of parameters with average of estimation errors over all pRF parameters:



Accuracy maps when estimating with linear HRF with optimized parameters for size and rotation:



DISCUSSION

We found that non-linearity in simulation HRFs may lead to erroneous pRF estimations. However, we showed that it is possible to optimize the stimulus parameters to ameliorate the effect of this non-linearity.

Therefore, we highly recommend that the stimulation protocol (i.e., stimulation and experiment parameters) should be fine-tuned using computer simulations before an actual fMRI experiment is conducted.

REFERENCES

[1] S. Dumoulin, B. Wandell. Population Receptive Field Estimates in Human Visual Cortex. In *NeuroImage '08*

[2] K. Kay and J. Winawer et all. Compressive Spatial Summation in Human Visual Cortex. In *Journal of Neurophysiology '13*

SOURCE CODE

The Python *prfsim* package can directly be installed from PyPI: 'pip install prfsim'
The source code is available at,
`github.com/arash-ash/pRFsim`