Neural, Spectral, and Psychophysical Consequences of Saccades

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APLab Meeting

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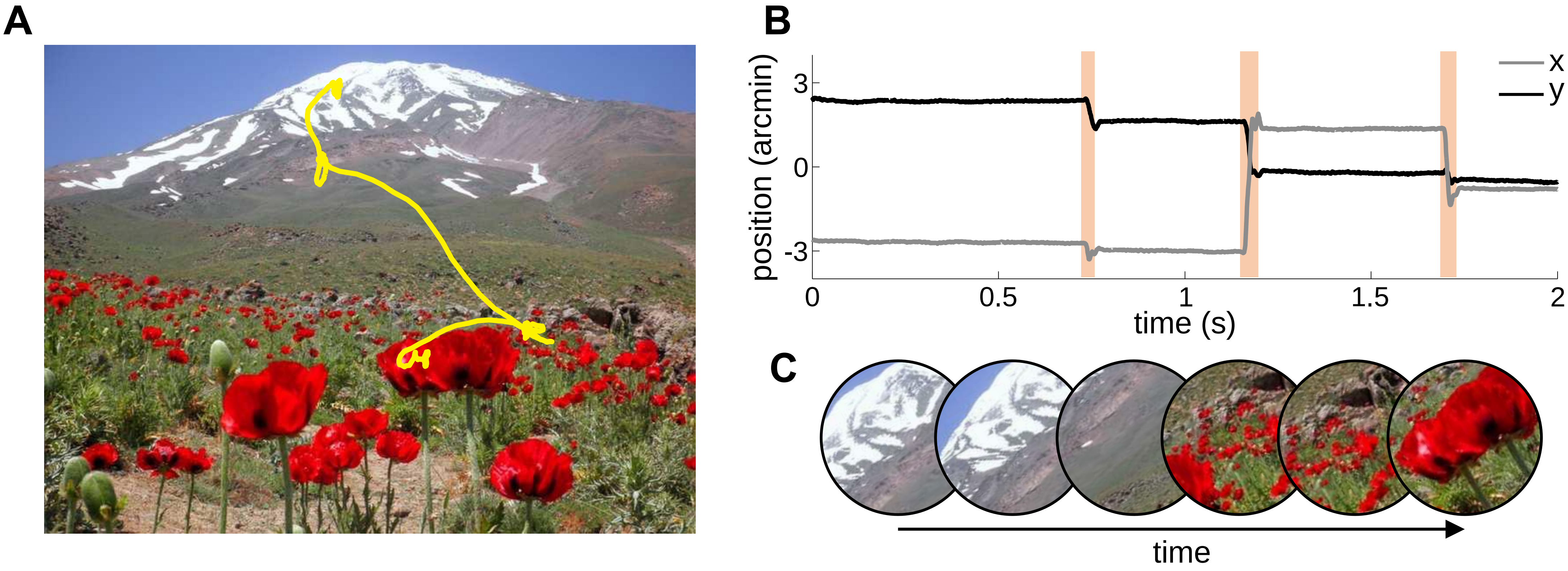
Outline

1. Neural and perceptual consequences of saccades
2. Space-time characteristics of saccade transients
3. Saccade Model
4. Next Steps

Saccades relocate gaze



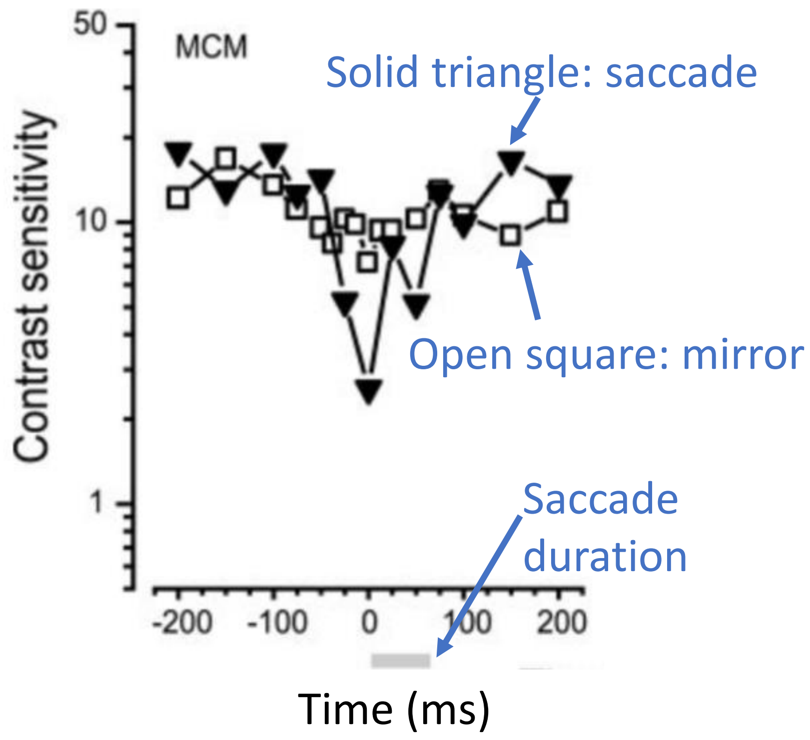
Saccade suppression and enhancement

Displacement suppression:

The displacement is visible if stimulus is off and back on again (Deubel et al., 1996), or has slight changes in its shape (Demeyer et al., 2010)

Decrease of contrast sensitivity (Diamond et al., 2000):

Stimulus 0.04 cpd (?), flash one frame (8.3 ms) at different time point in the saccade duration.



Saccade suppression and enhancement

LGN: weak suppression followed by strong enhancement.

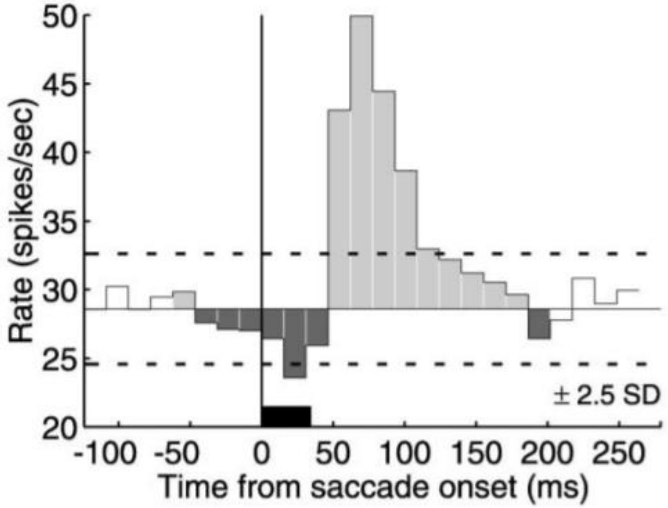
1. The modulation is **extraretinal**.
2. The modulation is independent from saccade size
3. The modulation is much stronger and more common in M cells. P cells show saccadic enhancement to the colored stimulus.

V1: inherit from LGN
extraretinal (no stim)

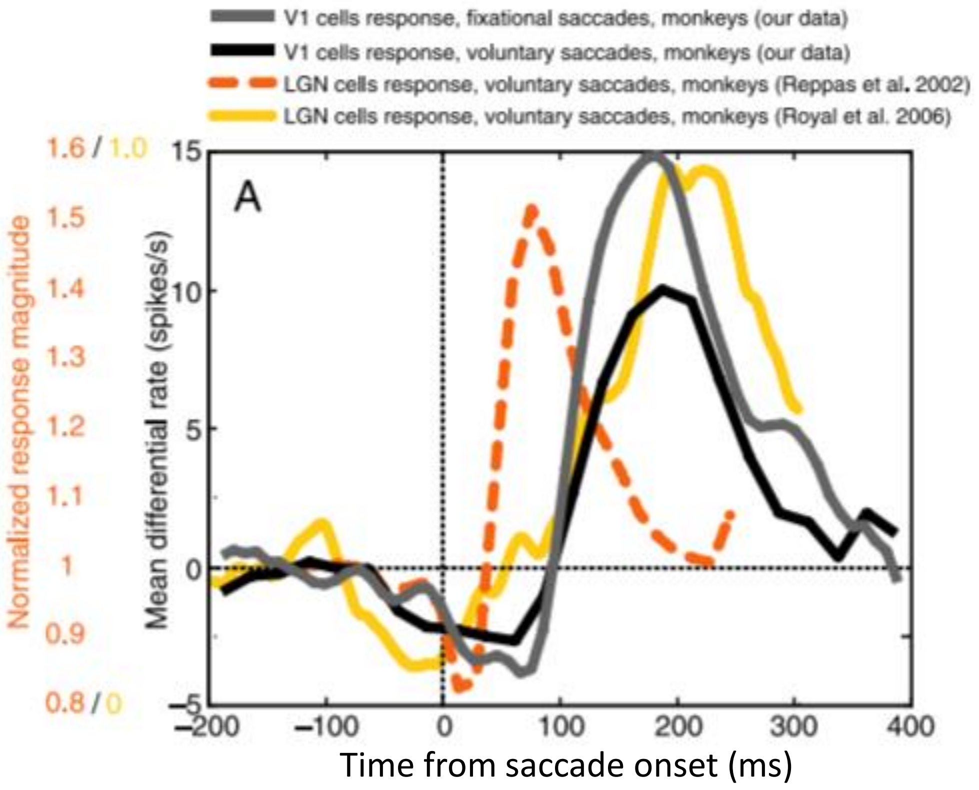
Other areas that follow the similar pattern: V4, MT, MST, VIP

Areas follow suppression + recovery pattern: SC, LIP

Response of a single M cell during 12 degree saccade

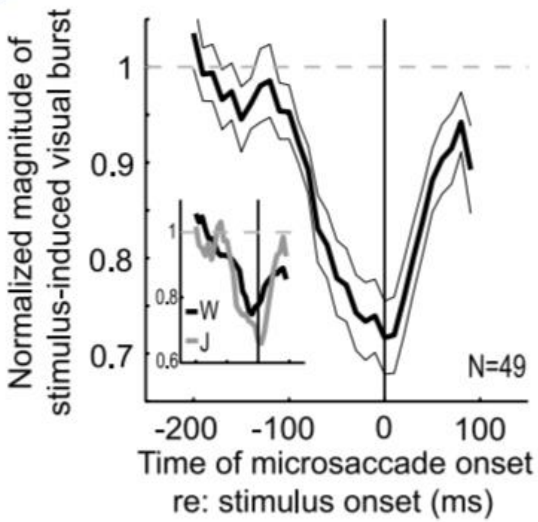


(Reppas et al., 2002)



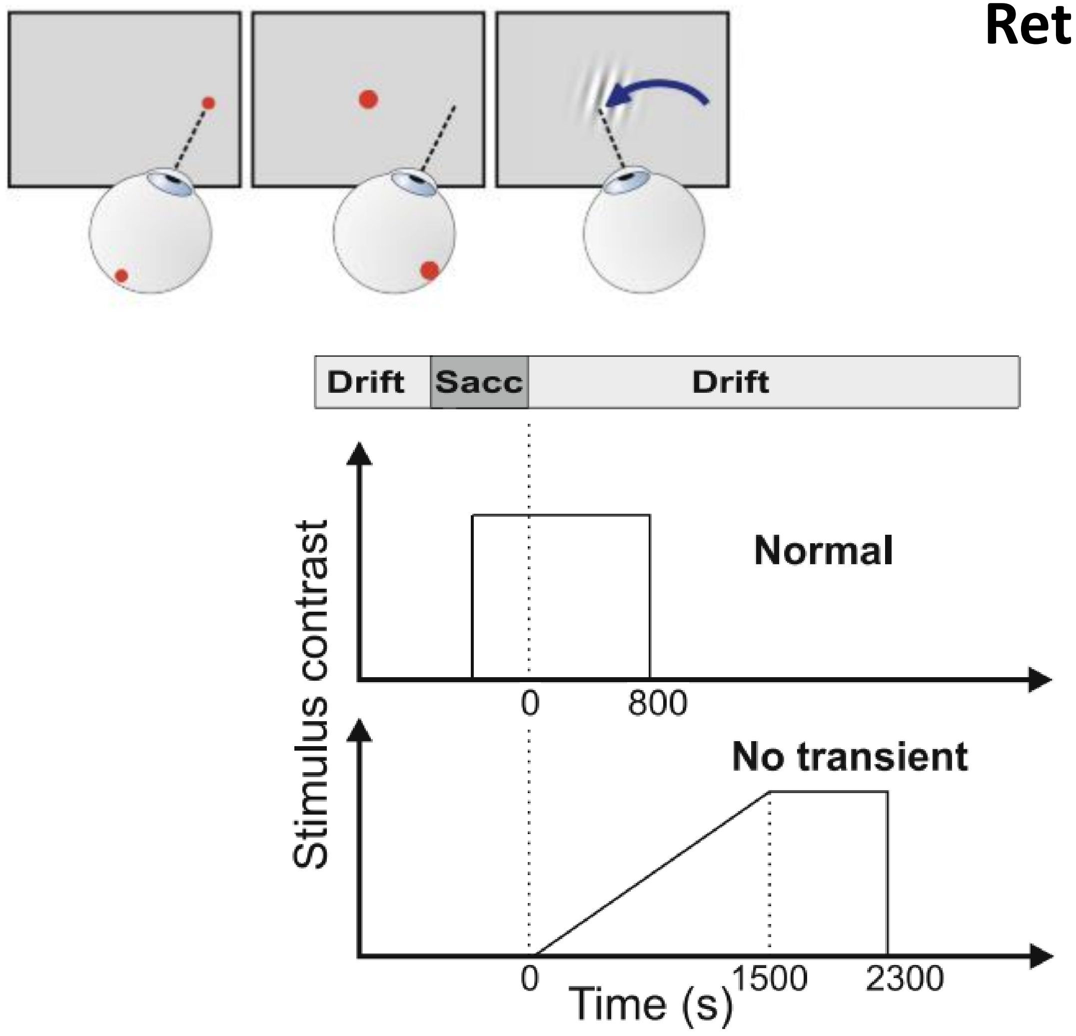
(Kagan et al., 2008)

SC response in microsaccade

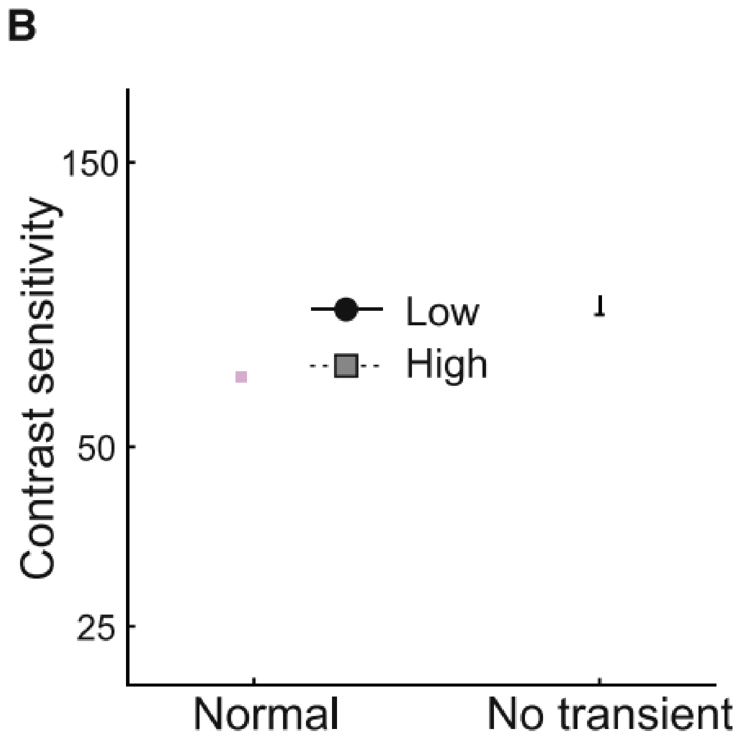


(Hafed & Krauzlis, 2010)

Perceptual consequences of saccade transients



Retinal enhancement of low spatial frequencies



Boi et al, 2017

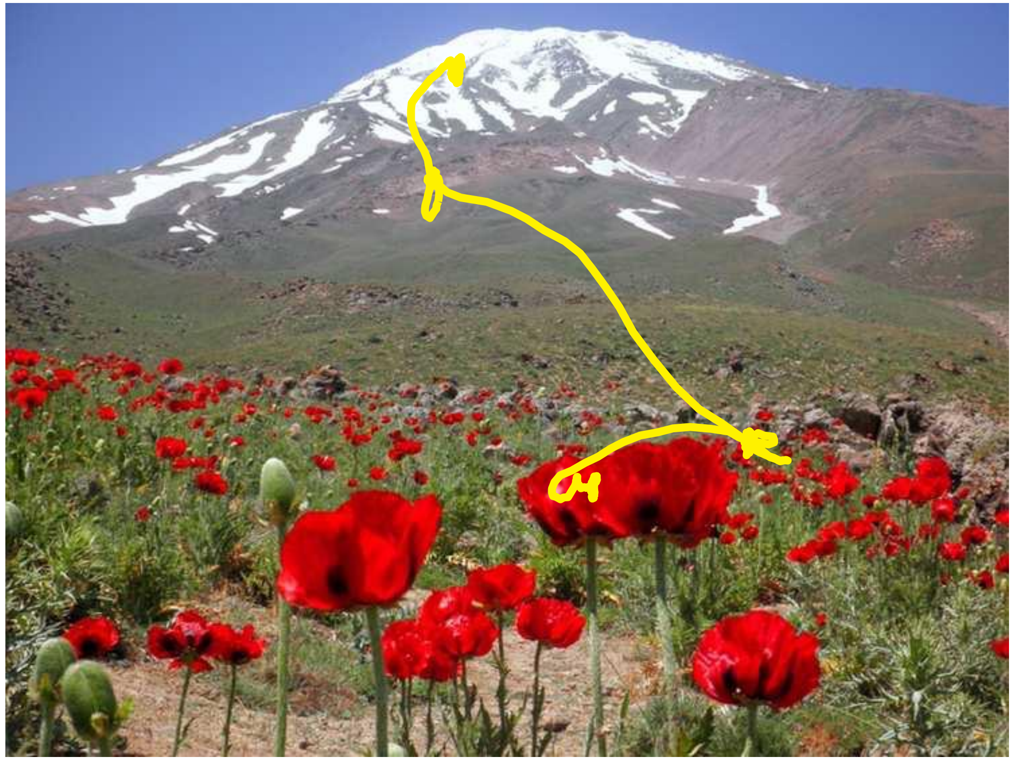
Saccades transform space into space-time

Space-time characteristics of saccade transients

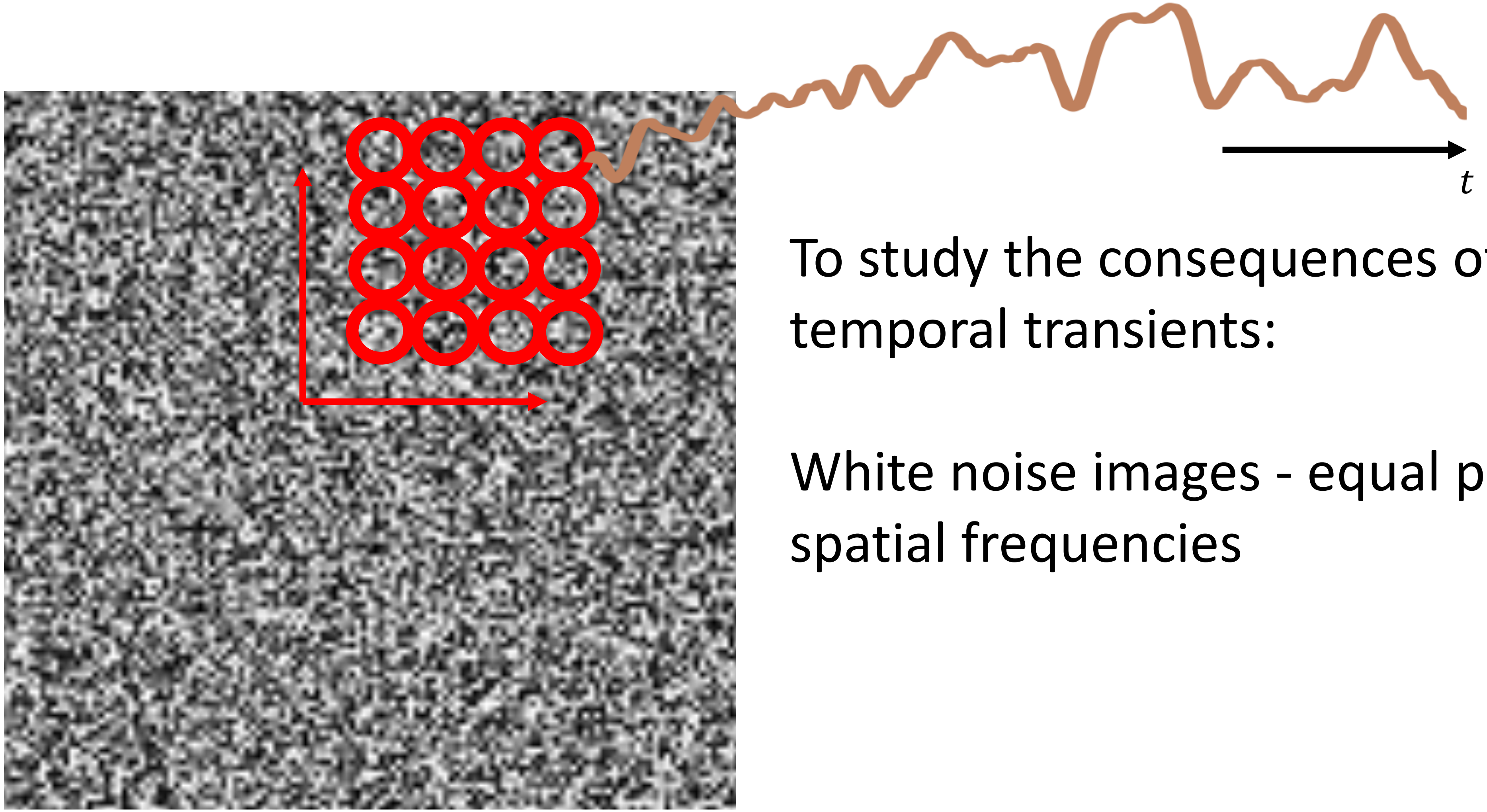
- Mostofi et al (in prep)

- Oculomotor activity recorded from N=14 subjects during free-viewing of natural scenes

A



Reconstructing retinal input

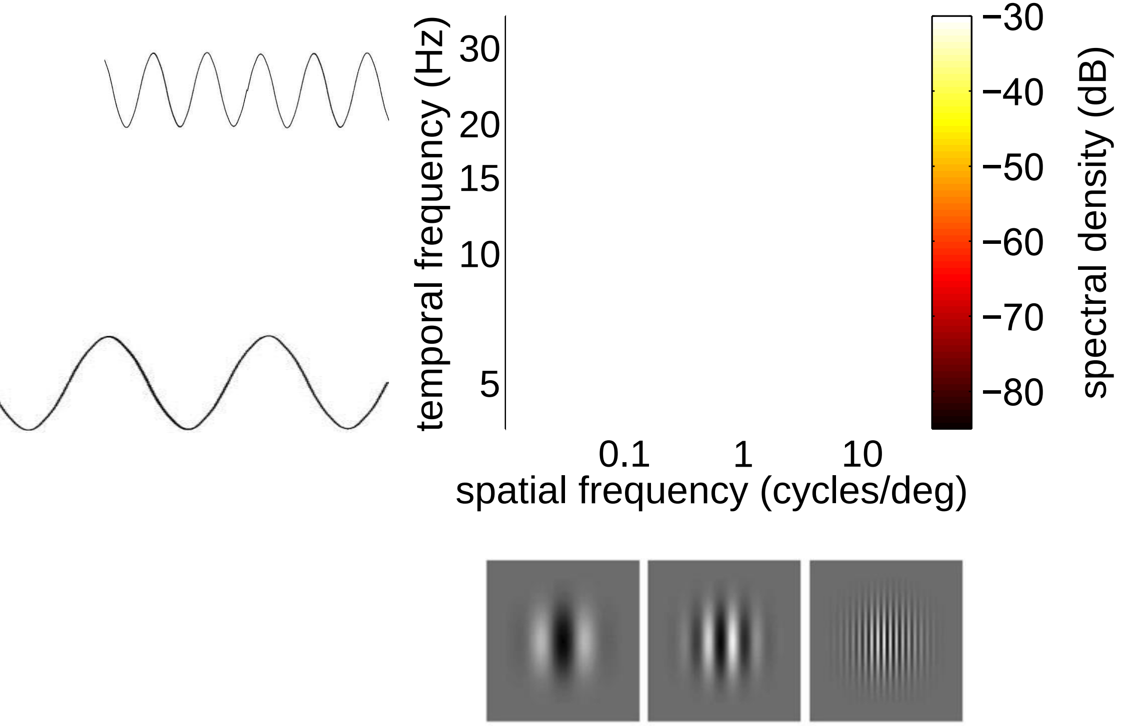


To study the consequences of saccade temporal transients:

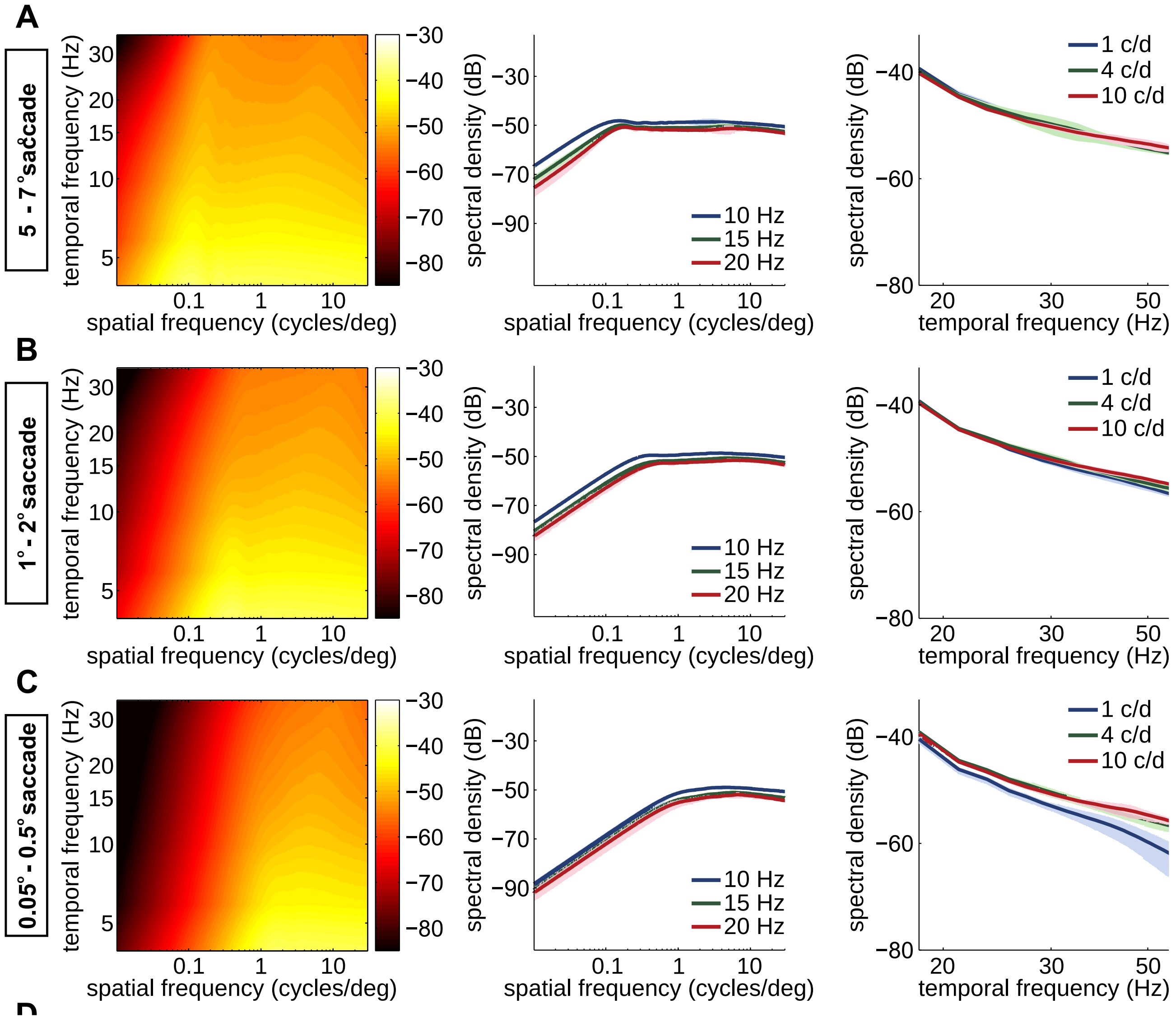
White noise images - equal power at all spatial frequencies

Frequency Content of Saccade Transients

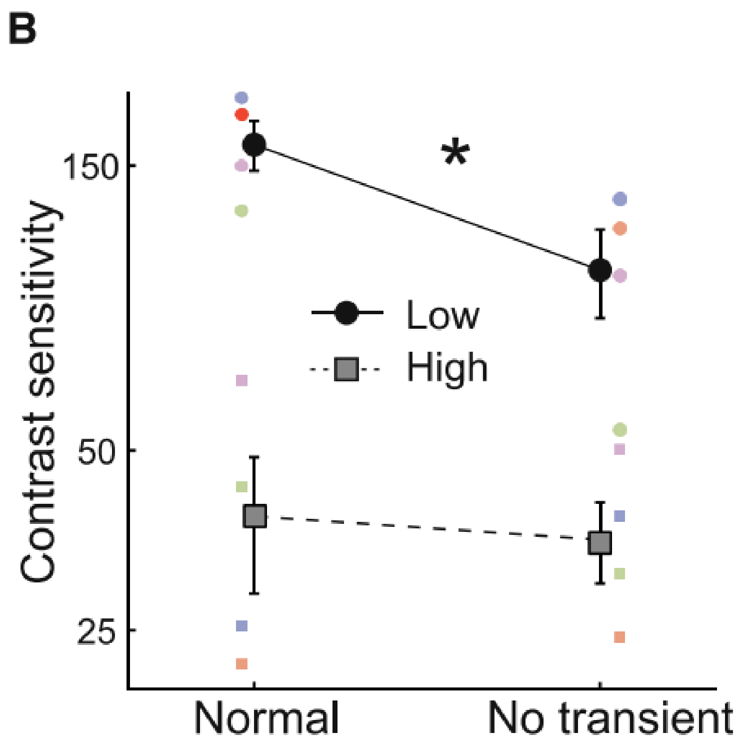
1-2deg saccades



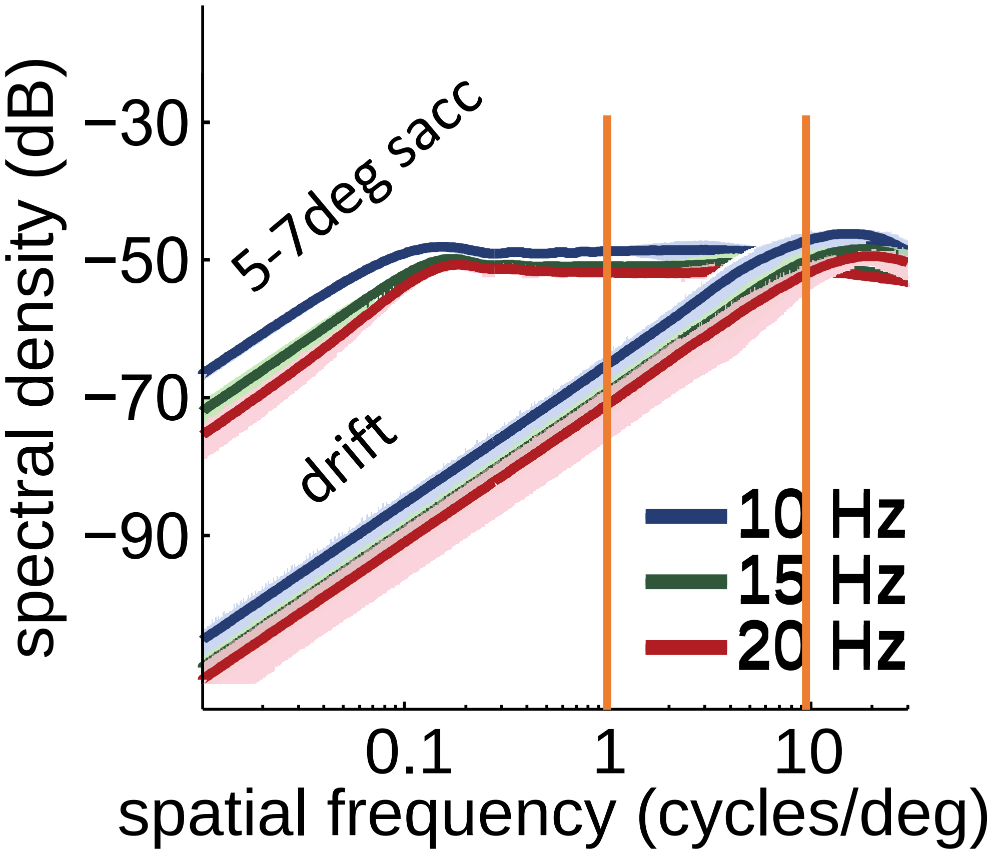
Frequency Content of Saccade Transients



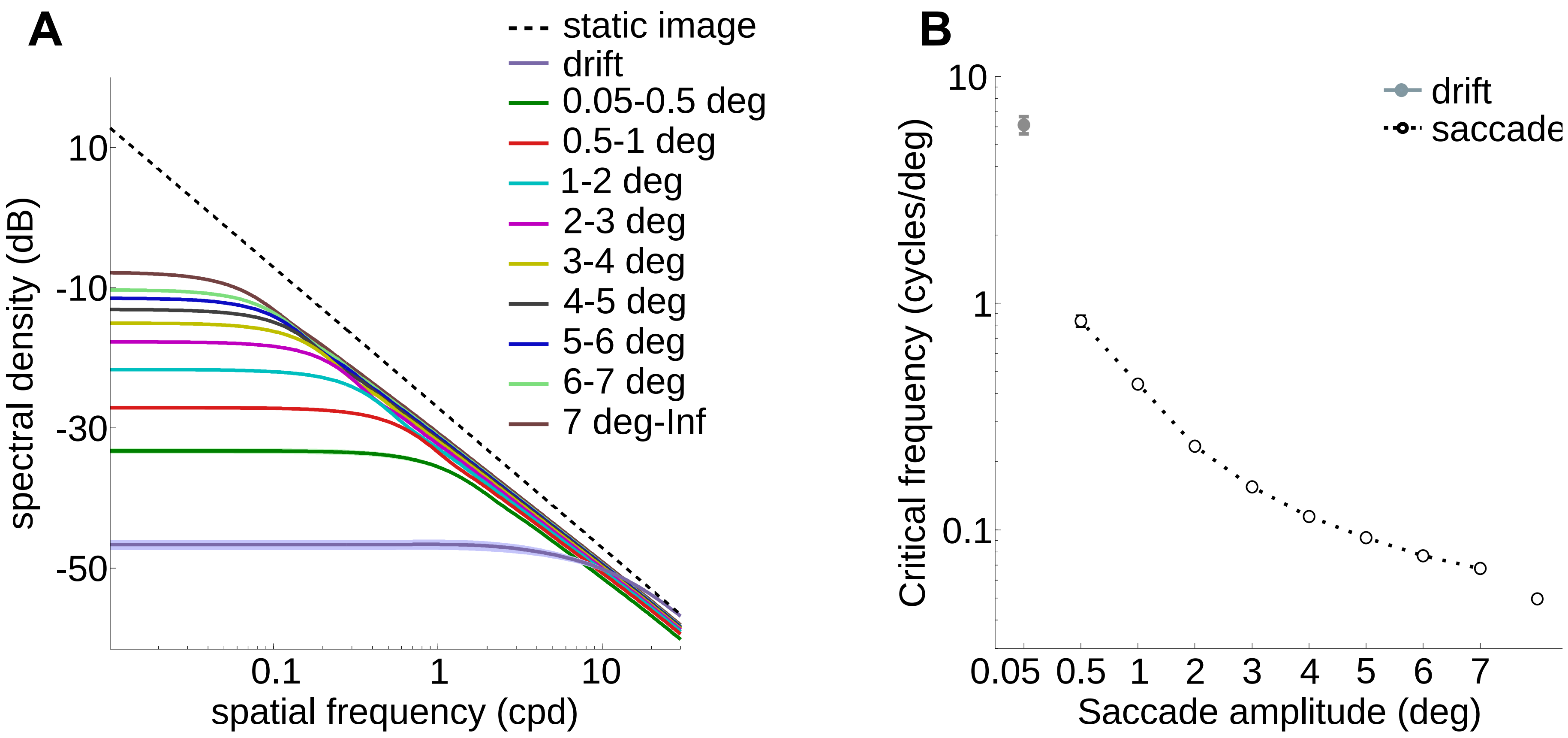
Consistent with psychophysical results



Boi et al, 2017

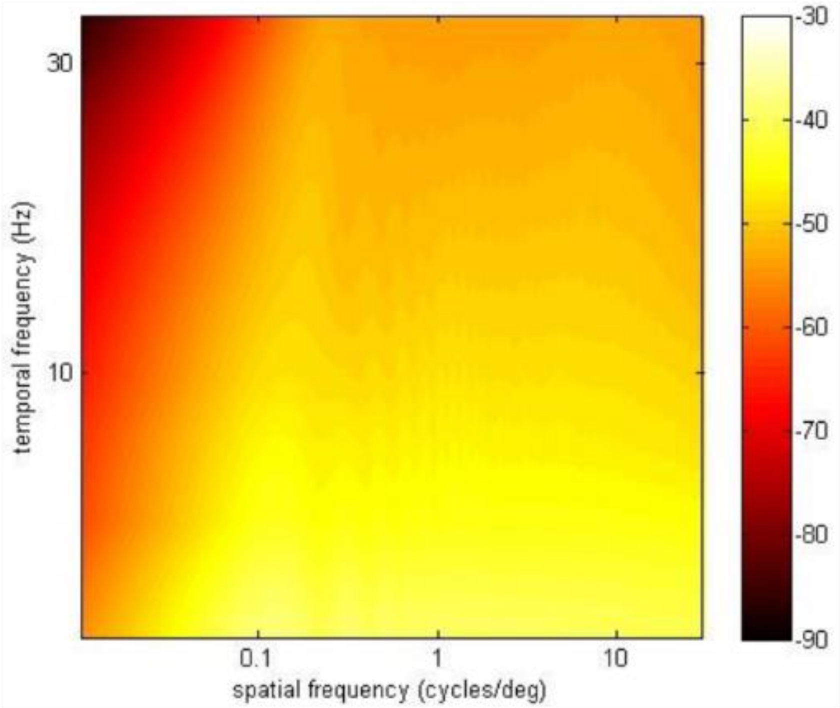


Spectral Consequences of Saccades

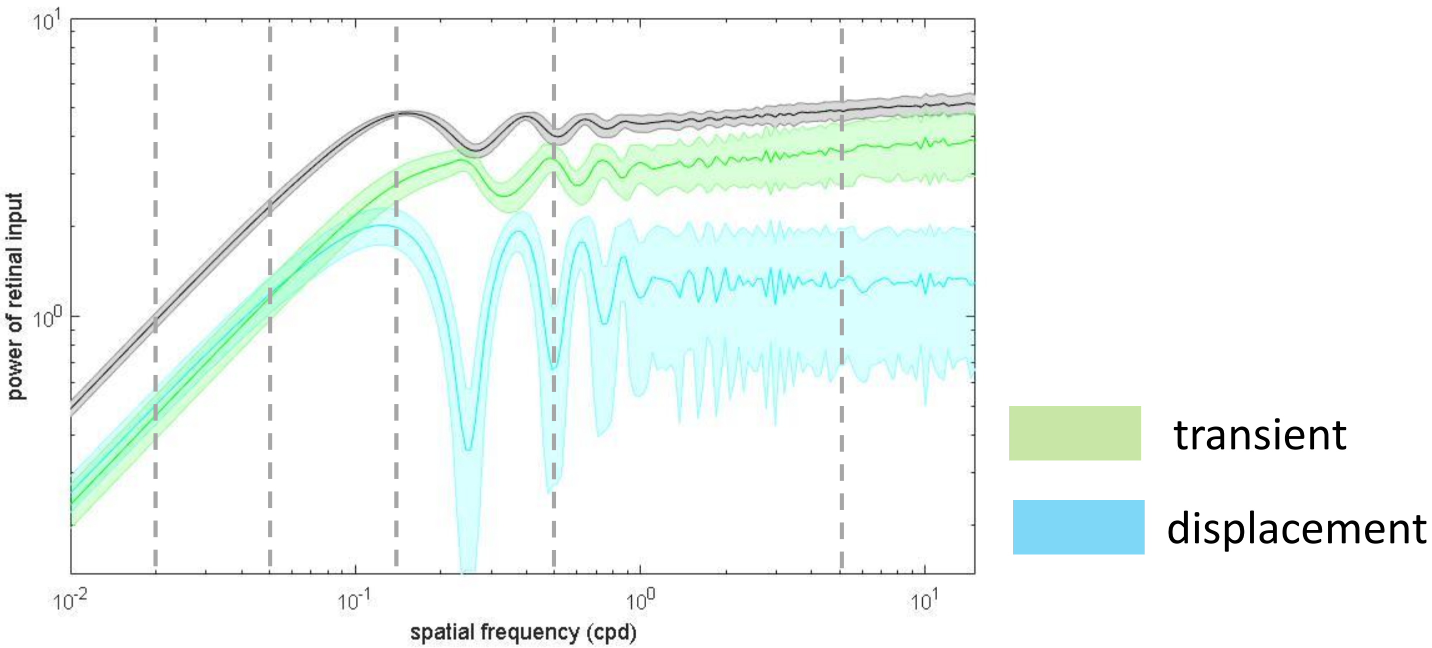


Saccade Model

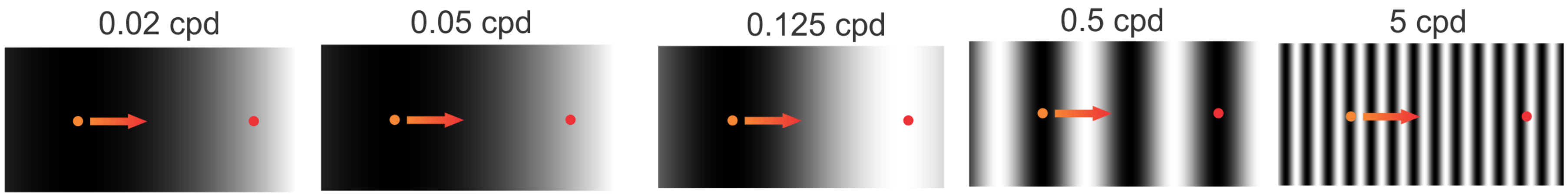
Why there are two regimes



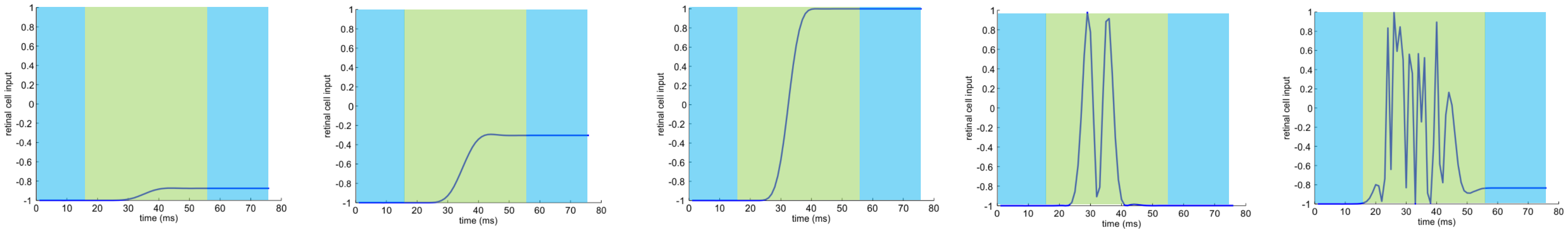
Power starts to saturate after 1/2A



Impose a 4 degree saccade on different gratings



Input of a photon receptor



Input power reformatting by saccade

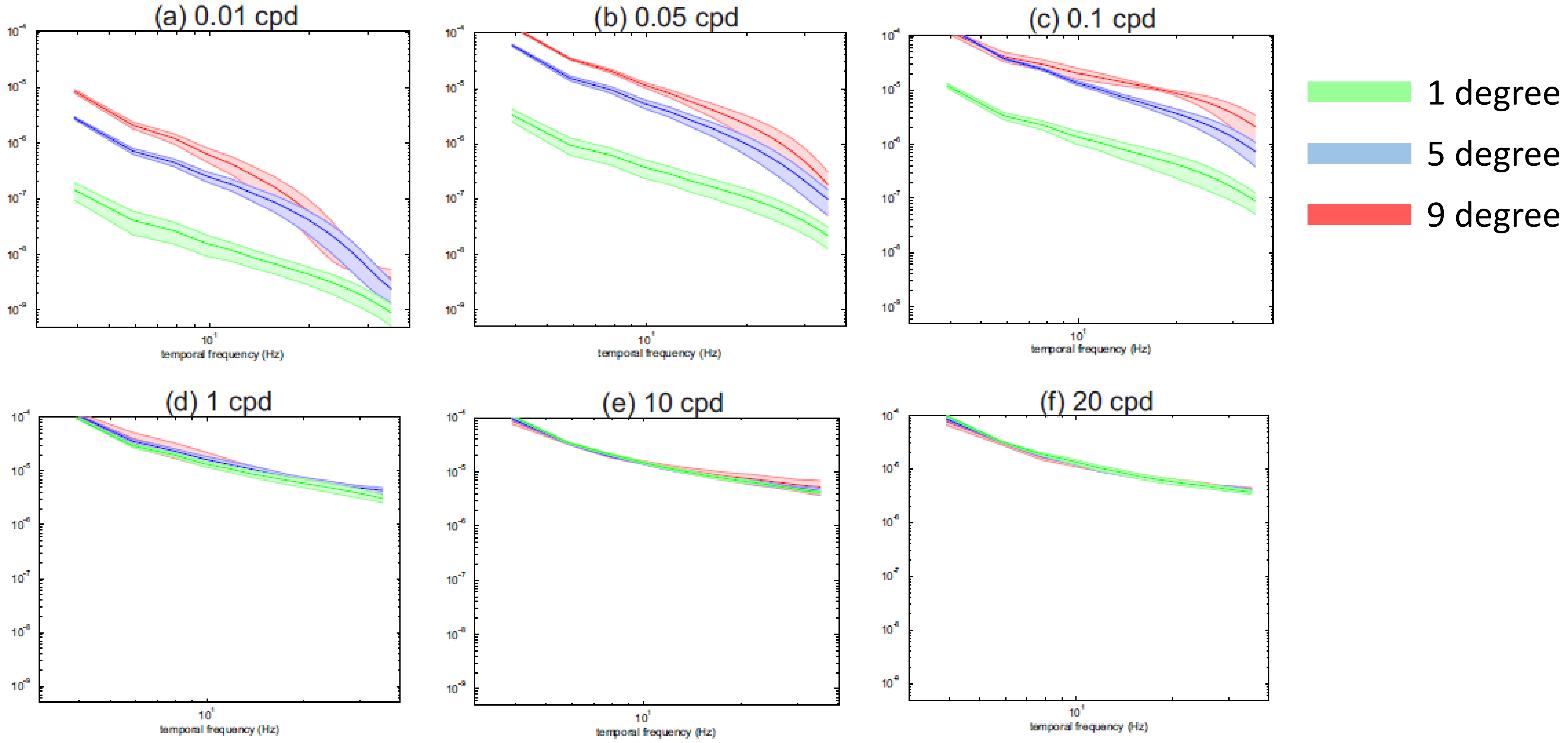
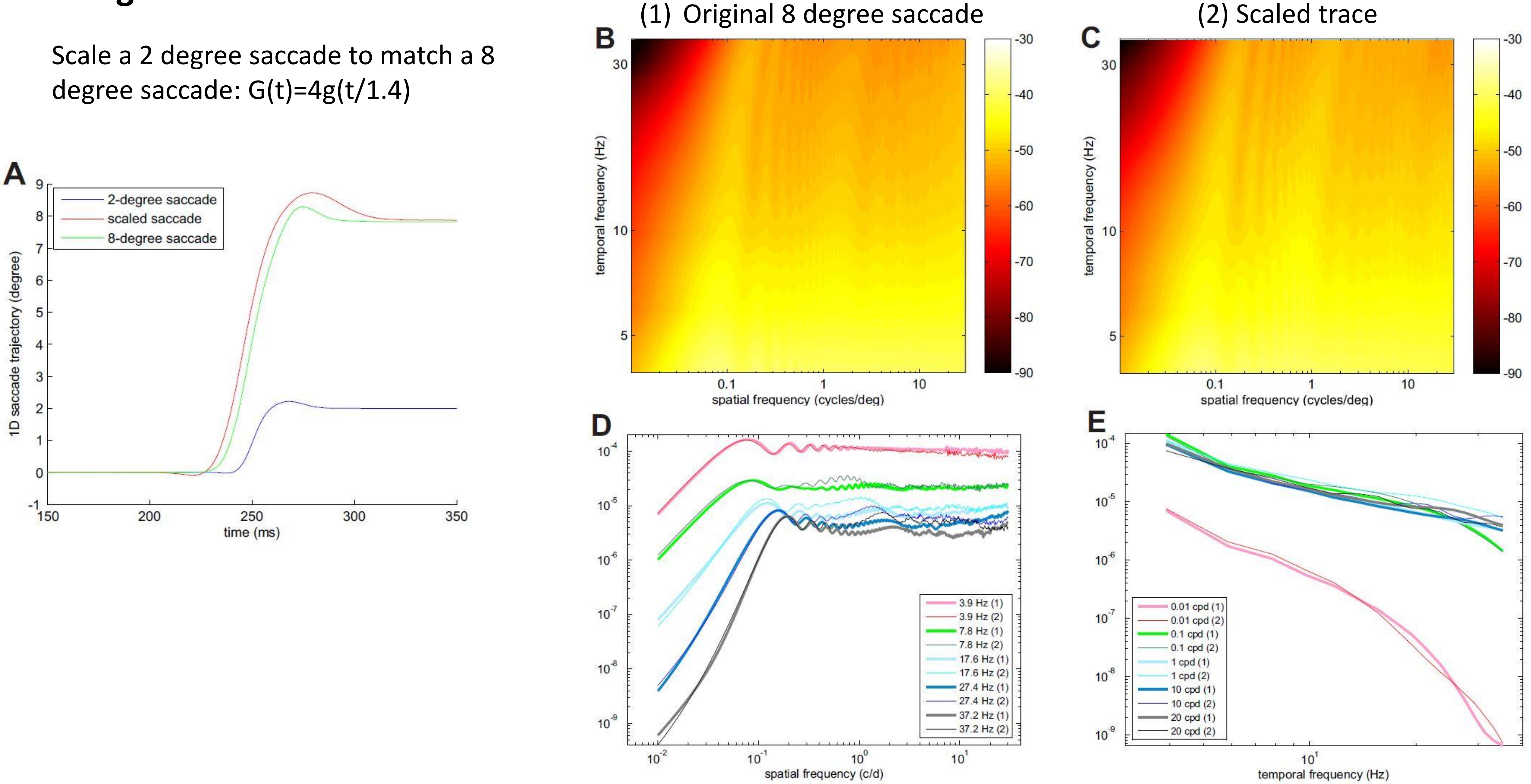


Figure 2: temporal power distribution comparison between different sizes of saccades: 1 degree (green); 5 degree (blue); 9 degree (red).

Why the saturated temporal power distribution unchanged across different sizes of saccades

Scale a 2 degree saccade to match a 8 degree saccade: G(t)=4g(t/1.4)

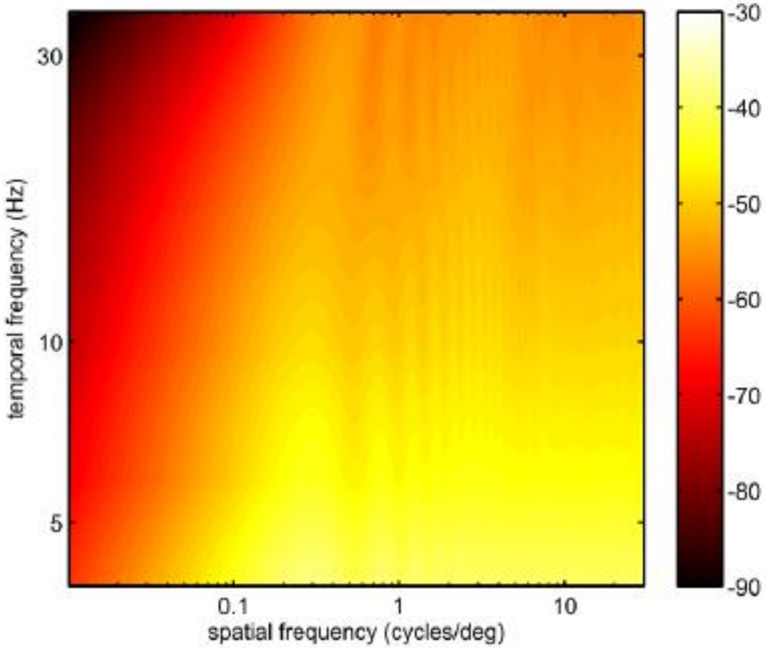


Scale in space

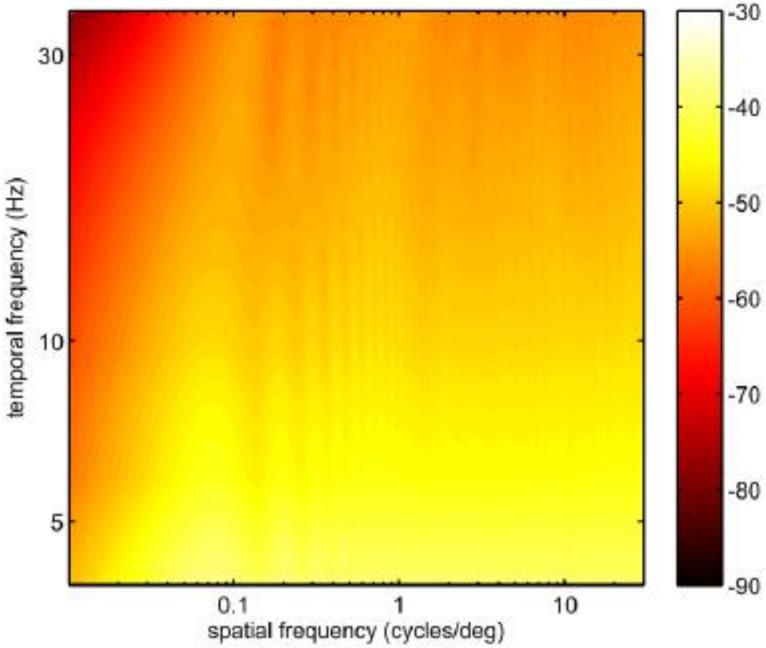
$$PSD(A \cdot g(t), k, \omega) = PSD(g(t), A \cdot k, \omega)$$

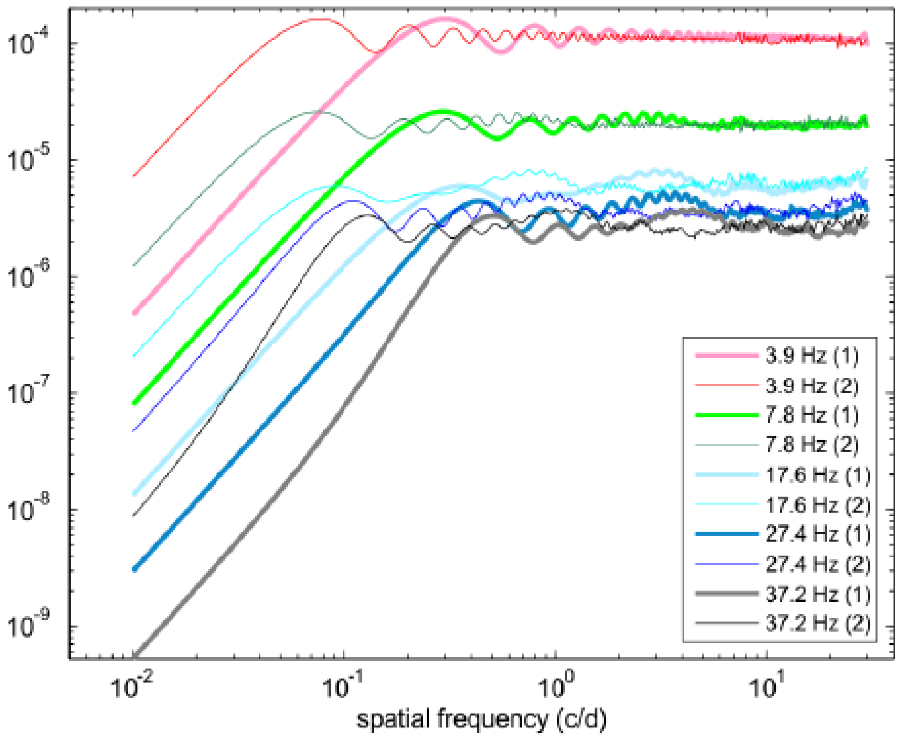
Horizontal shift doesn't change the saturated temporal power distribution

(1) Original 2 deg saccade: g(t)



(2) 4g(t)





Scale in time

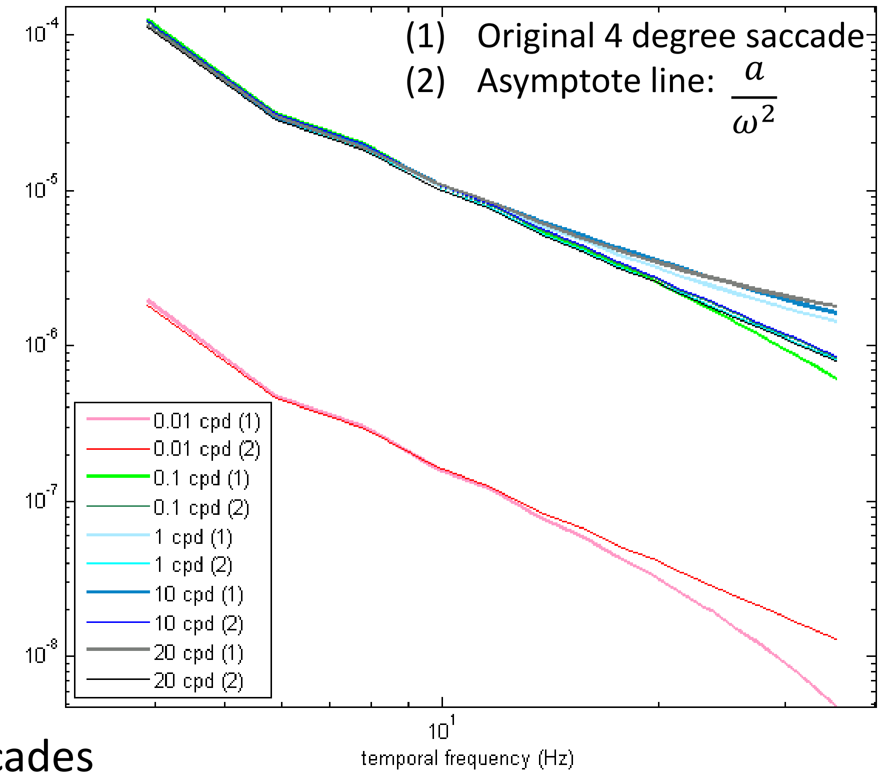
$$PSD(g(\psi \cdot t), k, \omega) = \frac{1}{\psi^2} PSD(g(t), k, \omega/\psi)$$

At low temporal frequency:

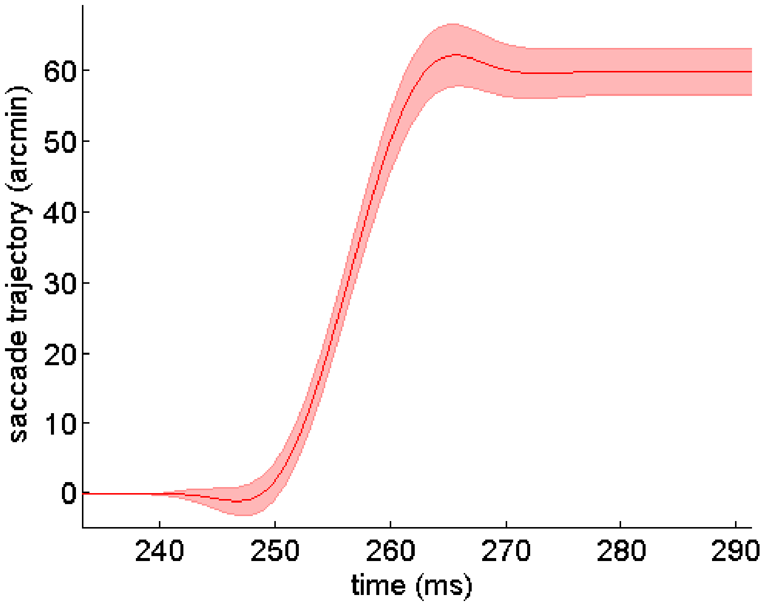
$$PSD(\omega) \propto \frac{1}{\omega^2}$$

At high temporal frequency:

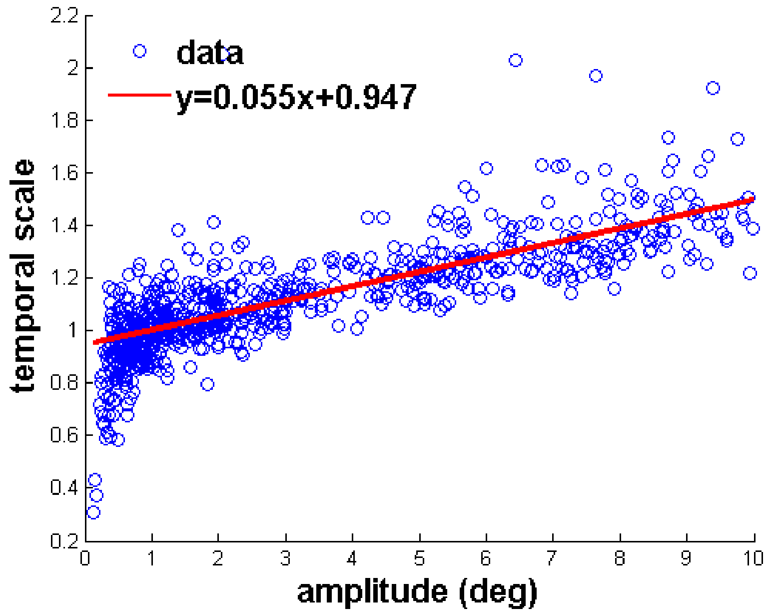
the temporal scalar is close to 1 because of the main sequence



1-degree saccade as the reference



Temporal scale for different sizes of saccades



Brief Summary:

For a single saccade: whitening + saturation regimes

- **Before 1/2A**, the temporal power introduced by both the displacement and transit of the saccade systematically increase with the spatial frequency.
- **After 1/2A**, the temporal power introduced by displacement oscillates but the major part of the temporal power is created by saccade transient, which saturates.

Across different sizes of saccades: the temporal pattern in saturation regimes doesn't change with saccade size.

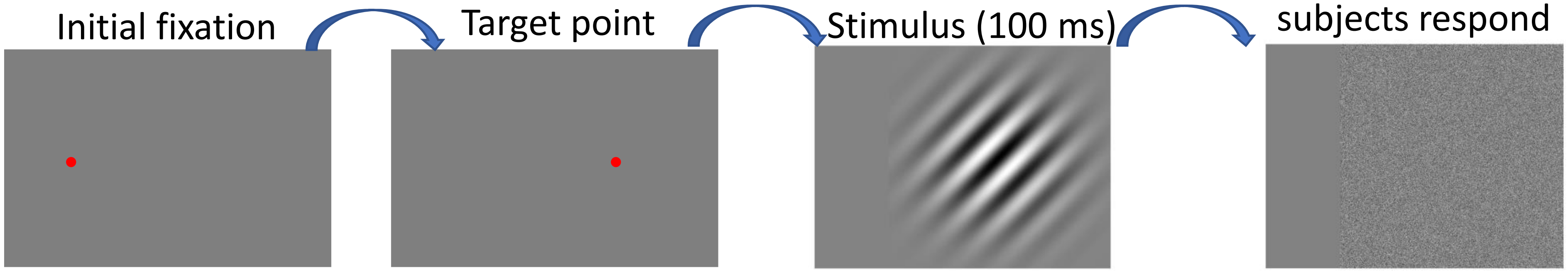
- **Spatial scaling** shifts the PSD horizontally (in log scale), .
- **Temporal scaling** doesn't change PSD in low temporal frequency (up to 10 Hz). It changes PSD by a minimum amount due to the main sequence.

Next Steps

Saccade experiment

Compare the temporal modulations of retina input generated by different sizes of saccades.
The temporal modulation pattern is tested by contrast sensitivity measured at three different spatial frequencies

Q1: Whether the retinal input in the whole saccade procedure contributes to perception?
Q2: If not, which temporal kernel will fit the data best?



Saccade sizes: 1 degree, 6.75 degree

Grating frequencies: 0.15 cpd, 1 cpd, 4 cpd (45 degree tilted,)

Control group: 1. flash the stimulus at saccade offset (compare to large saccade)
2. flash the stimulus during fixation (compare to small saccade)

Extra Slides

Stimulus image: $I = cos(2\pi f x)$
Eye movement: $\triangle x = g(t)$
Retinal input sequence: $r(x,t) = cos(2\pi f(x + g(t)))$

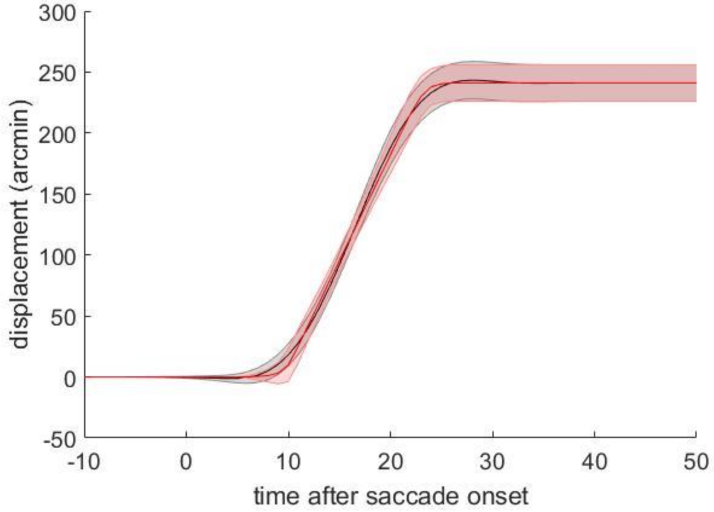
$$
\begin{aligned}
R(k,\omega) &= \iint_{-\infty}^{\infty} r(x,t) e^{-j2\pi(kx+\omega t)} dxdt \\
&= \iint_{-\infty}^{\infty} \frac{1}{2}(e^{j2\pi f(x+g(t))} + e^{-j2\pi f(x+g(t))}) e^{-j2\pi(kx+\omega t)} dxdt \\
&= \frac{1}{2} \iint_{-\infty}^{\infty} e^{j2\pi f x} e^{j2\pi f g(t)} e^{-j2\pi k x} e^{-j2\pi \omega t} dxdt + negativeTerm \\
&= \frac{1}{2} \int_{-\infty}^{\infty} e^{j2\pi(f-k)x} dx \int_{-\infty}^{\infty} e^{j2\pi(fg(t)-\omega t)} dt + negativeTerm \\
&= \frac{\delta(k) \ + \delta(-k)}{2} \mathcal{F}(e^{j2\pi f g(t)})
\end{aligned}
$$

Ramp model

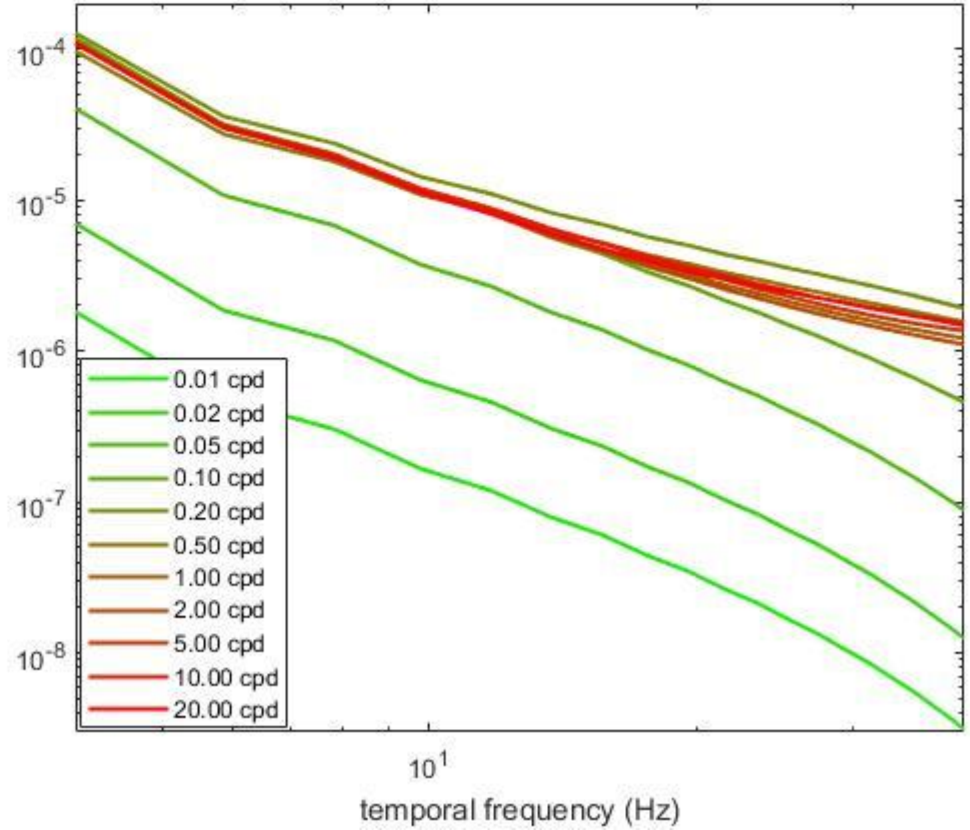
$$g(t) = \begin{cases} 0, & t \leqslant t_0 \\ v(t - t_0), & t_0 < t \leqslant t_0 + A/v \\ A, & t > t_0 + A/v \end{cases}$$

Parallel power $|R(k,\omega)|^2 = (\frac{kA}{\omega})^2 (sinc(kA - \omega\frac{A}{v}))^2$

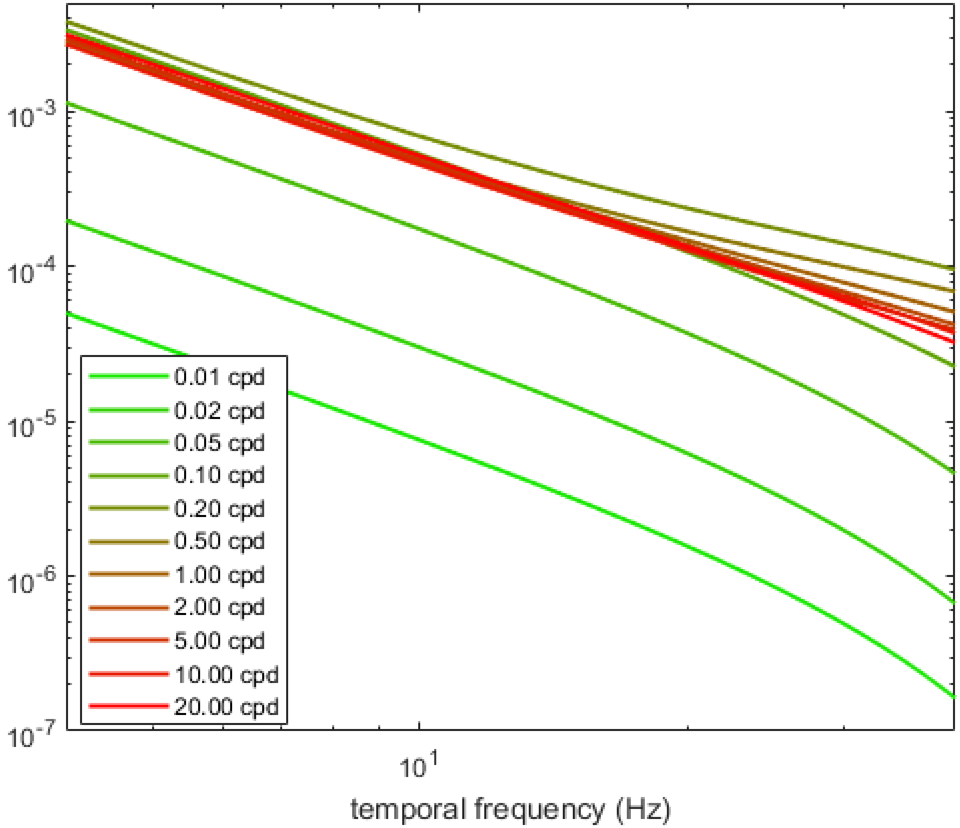
Radial average $|R(k,\omega)|^2 = \int_0^{2\pi} (\frac{kA\cos\theta}{\omega})^2 (sinc(kA\cos\theta - \frac{A\omega}{v}))^2 d\theta$



4 degree saccade



Ramp closed form *A*=4 degree, *v*=289 degree/sec



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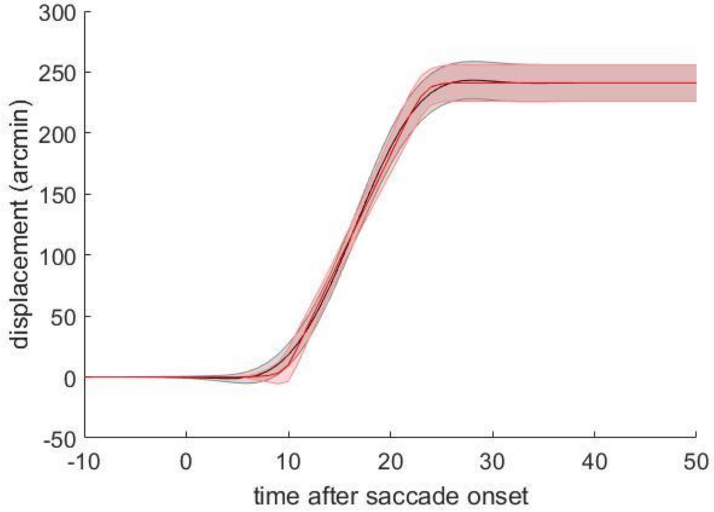
Radial average $|R(k,\omega)|^2 = \int_0^{2\pi} (\frac{kA\cos\theta}{\omega})^2 (sinc(kA\cos\theta - \frac{A\omega}{v}))^2 d\theta$



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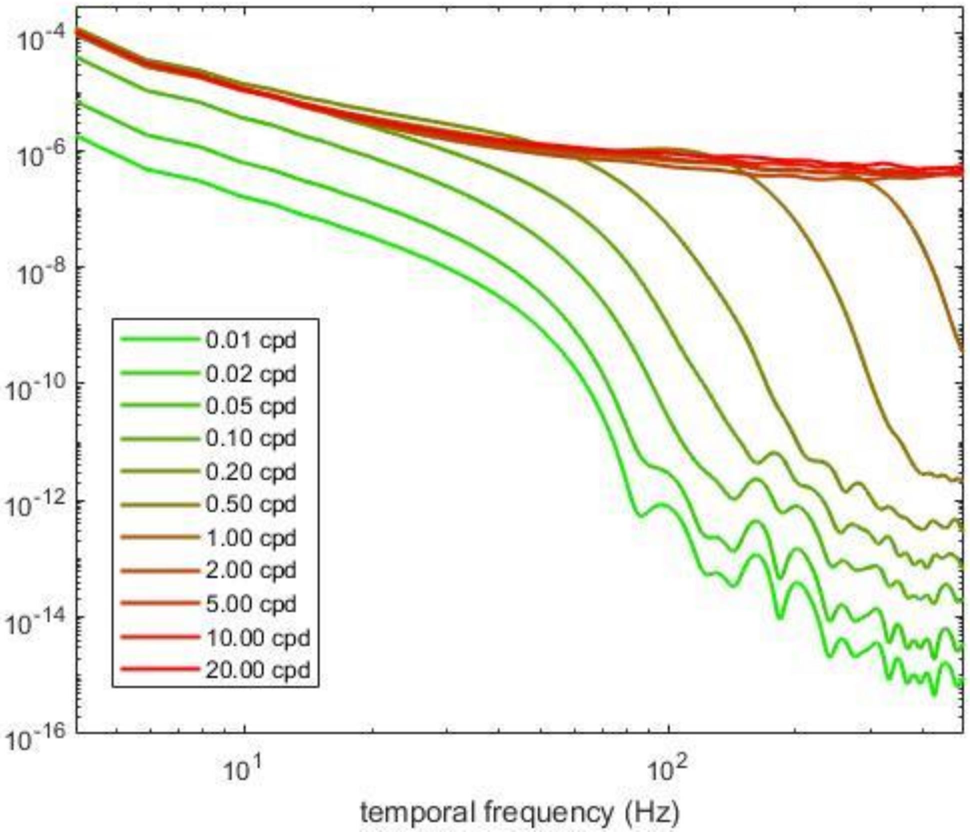

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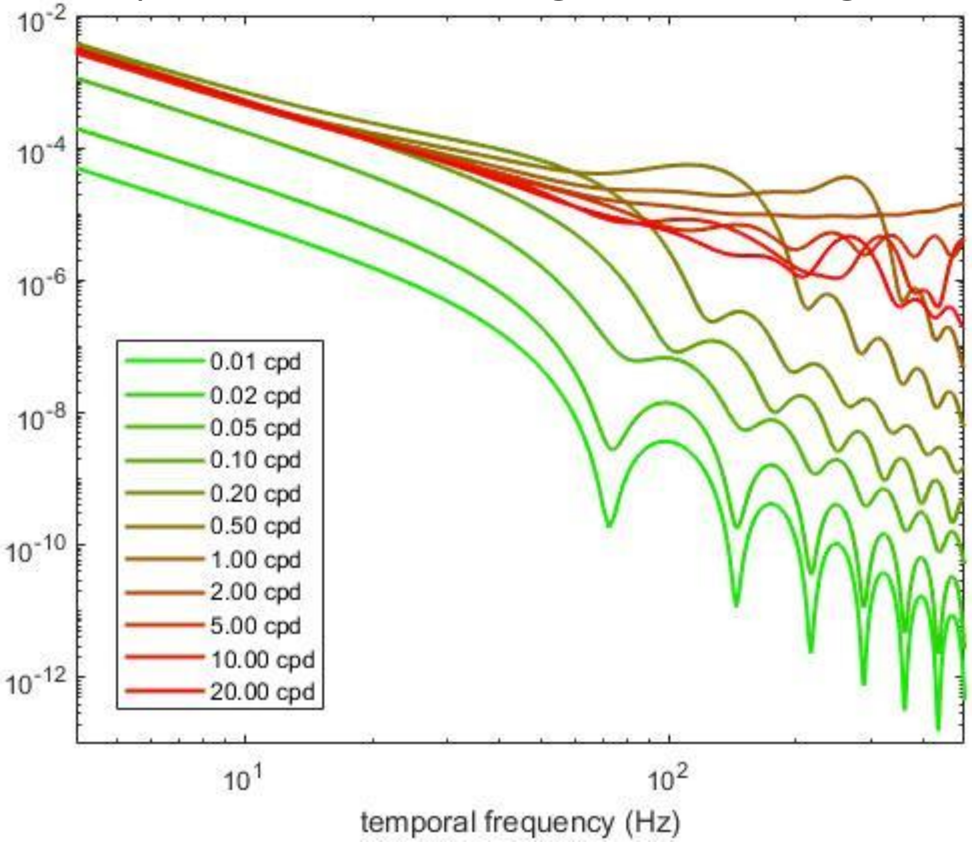

For spatial scaling, $\triangle x = G(t) = A \cdot g(t)$

$$\begin{aligned} R(f, A \cdot g(t), k, \omega) &= \frac{1}{2} \int_{-\infty}^{\infty} e^{j2\pi(f-k)x} dx \int_{-\infty}^{\infty} e^{j2\pi(fG(t)-\omega t)} dt + negativeTerm \\ &= \frac{1}{2} \int_{-\infty}^{\infty} e^{j2\pi(f-k)x} dx \int_{-\infty}^{\infty} e^{j2\pi((f \cdot A)g(t)-\omega t)} dt + negativeTerm \\ &= \frac{1}{2} \int_{-\infty}^{\infty} e^{j2\pi(f \cdot A - k \cdot A)/A \cdot x} dx \int_{-\infty}^{\infty} e^{j2\pi((f \cdot A)g(t)-\omega t)} dt + negativeTerm \end{aligned}$$

$$\begin{aligned} R(A \cdot g(t), k, \omega) &= \frac{1}{2} \delta(k) \int_{-\infty}^{\infty} e^{j2\pi((A \cdot k)g(t)-\omega t)} dt + negativeTerm \\ &= R(g(t), A \cdot k, \omega) \end{aligned}$$

$$PSD(A \cdot g(t), k, \omega) = PSD(g(t), A \cdot k, \omega)$$

For temporal scaling, $\triangle x = G(t) = g(\psi \cdot t)$

$$
\begin{aligned}
R(f, g(\psi \cdot t), k, \omega) &= \frac{1}{2}\int_{-\infty}^{\infty} e^{j2\pi(f-k)x} dx \int_{-\infty}^{\infty} e^{j2\pi(f \cdot g(\psi \cdot t) - \omega t)} dt + negativeTerm \\
&= \frac{1}{2}\int_{-\infty}^{\infty} e^{j2\pi(f-k)x} dx \int_{-\infty}^{\infty} e^{j2\pi(f \cdot g(\psi \cdot t) - \omega(\psi \cdot t)/\psi)} d(\psi t) \frac{dt}{d(\psi t)} + negativeTerm \\
&= \frac{1}{2}\int_{-\infty}^{\infty} e^{j2\pi(f-k)x} dx \frac{1}{\psi}\int_{-\infty}^{\infty} e^{j2\pi(f \cdot g(T) - \omega T/\psi)} dT + negativeTerm
\end{aligned}
$$

$$
\begin{aligned}
R(g(\psi \cdot t), k, \omega) &= \frac{1}{2}\delta(k)\frac{1}{\psi}\int_{-\infty}^{\infty} e^{j2\pi(k \cdot g(T) - \omega T/\psi)} dT + negativeTerm \\
&= \frac{1}{\psi} R(g(t), k, \omega/\psi)
\end{aligned}
$$

$$
PSD(g(\psi \cdot t), k, \omega) = \frac{1}{\psi^2} PSD(g(t), k, \omega/\psi)
$$

Comparison of Direct and Indirect Methods