

## SUPPLEMENTAL MATERIAL

### ***Different models for perisaccadic localization errors.***

As described in Introduction and Discussion, several models have been proposed to account for the dynamic pattern of perisaccadic localization errors. All models have in common that the errors arise as a result of errors in the visuomotor transformation that updates the initial retinal target coordinates with an efference copy of the oculomotor command into an oculocentric motor error signal. For the visuomotor system to work properly, the target should be updated according to:

$$\vec{S}_2 = \vec{R}_2(T_0) - \Delta\vec{E}_1(T_0) \quad (\text{S1})$$

with  $R_2(T_0)$  the retinal error of the second target  $V_2$  at time  $T_0$  of the flash,  $\Delta E_1(T_0)$  the subsequent eye-displacement vector toward the first target  $V_1$  following the target flash (note: not necessarily equal to the first saccade, as  $V_2$  may be presented during the saccade), and  $S_2$  the saccade required to look at the second target (the motor error vector). Note that the motor error can also be computed from position signals, in which case

$$\vec{S}_2 = \vec{T}_2(T_0) - \vec{E}_1(\text{end}) \quad \text{with} \quad \vec{T}_2(T_0) = \vec{R}_2(T_0) + \vec{E}_1(T_0) \quad (\text{S2})$$

with  $T_2(T_0)$  the target in head-centered coordinates, and  $E_1(t)$  the eye positions at the time of the target flash, and at the end of the first saccade, respectively.

#### ***Dassonville’s model***

In the model proposed by Dassonville et al. (1992) localization errors arise because of a discrepancy between the actual eye-in-head position,  $E(t)$ , and the internal representation of eye position signal,  $E^{int}(t)$ . The latter is supposed to lead the former by  $T_{lead}$ , which is about 160 ms (the saccade programming epoch), but the representation of its trajectory is a low-pass filtered version of the actual trajectory:

$$E^{int}(t) = \int_0^{\infty} E(t + T_{lead} - \tau) \cdot h_s(\tau) d\tau \quad (\text{S3})$$

where the LP filter (time constant  $T_s$  and order  $n_s$ ) is given by:

$$h_s(\tau) = \frac{\tau^{n_s-1}}{(n_s-1)!} \cdot e^{-\tau/T_s} \quad (\text{S4})$$

The localization error arises, because the internal update process (Eqns. S1 or S2) is determined by

$$\vec{S}_2 = \vec{R}_2(T_0) - \Delta\vec{E}_1^{int}(T_0) \quad (\text{S5})$$

from which it follows that the expected error is in the direction of the first saccade, and given as:

$$E_{2, //}(T_0) = E^{\text{int}}(T_0) - E(T_0) \quad (\text{S6})$$

*Pola's model.*

Pola (2004) argued that the perisaccadic localization errors have a visual, rather than an oculomotor, origin. The probe stimulus,  $V_2$ , which is presented for a very brief time to sample the eye position, is in fact 'blurred' (i.e. LP filtered) within the visual system. As a result, the visual-perceptual system has no precise information about the eye position at the time of the flash, but is assumed to be based on a time average taken during the persistent visual activity. The visual probe stimulus  $V_2$  (duration  $D_v$  ms, presented at  $t=T_0$ ) is represented as a LP filtered version of the visual pulse. Thus, although the retinal stimulus is described as  $\vec{V}_2(t) = R(t) \cdot \vec{V}_2$ , with:

$$R(t) = \begin{cases} 1 & \text{for } 0 \leq t \leq D_v \\ 0 & \text{elsewhere} \end{cases} \quad (\text{S7})$$

the resulting visual activity has an internal delay  $T_{\text{lag}}$ , and is given by

$$R^{\text{int}}(t, T_0) = \int_0^{\infty} R(t - T_0 - T_{\text{lag}} - \tau) \cdot h_v(\tau) d\tau \quad (\text{S8})$$

with

$$h_v(\tau) = \frac{\tau^{n_v-1}}{(n_v-1)!} \cdot e^{-\tau/T_v} \quad (\text{S9})$$

In this idea, the neural representation of eye position is supposed to be accurate, apart from a short delay,  $T_{\text{delay}}$ , of a few tens of ms:  $E^{\text{int}}(t) = E(t - T_{\text{delay}})$ .

As a result, the *perceived eye position* at the time of the light flash is determined by the weighted temporal average of the internal visual and oculomotor signals (Pola, 2004):

$$E^{\text{perc}}(T_0) = \int_0^{\infty} R^{\text{int}}(t, T_0) \cdot E^{\text{int}}(t - T_{\text{delay}}) dt \quad (\text{S10})$$

Because the weighted averaged eye position signal is not equal to the actual eye position, a discrepancy arises, which again, through Eqn. S1 or S2 gives rise to a localization error found by Eqn. S6.

Note, that according to Eqn. S10 the perceived eye position differs from the internal eye position as a result of visual blurring. If the sensory stimulus would be *auditory*, this effect would be entirely absent (or at least very different). This contrasts with the Dassonville proposal (Eqn. S3), for which the stimulus modality is immaterial.

To find optimal parameters for these models (Dassonville's model:  $T_{\text{lead}}$ ,  $n_s$  and  $T_s$ ; Pola's model:  $T_{\text{delay}}$ ,  $T_{\text{lag}}$ ,  $T_v$  and  $n_v$ , and for a combined visual-motor version of this scheme, in which the internal eye position signal in Eqn. S10 is described by Eqn. S3, leading to six free parameters), we applied an iterative procedure (Nelder-Mead simplex direct search method) that minimized the mean squared error for all measured first-

saccade trajectories (pooled for the four amplitude series), which was implemented in Matlab 7.0 (The Mathworks Inc.).

*Ross et al. model.*

The model proposed by Ross et al. (1997) combines both aspects of the two previous models: (i) a sluggish version of the oculomotor command (in their study described by a slowly rising offset eye position,  $E^{int}(end)$ , and a slowly decaying onset eye position,  $E^{int}(T_0)$ , with essentially the same effect as Eqn. S3), and (ii) a visual field effect, in which the retinal representation undergoes a non-uniform (i.e. eccentricity-dependent, but nonlinear) compression toward the fovea which, in combination with the sluggish onset eye-position signal leads to a distorted representation of the target in head-centered coordinates (cf. Eqn. S2):

$$\vec{S}_2 = \vec{T}_2^{int}(T_0) - \vec{E}_1^{int}(end) \quad \text{with} \quad \vec{T}_2^{int}(T_0) = C(\vec{R}_2(T_0) \cdot \vec{R}_2 + \vec{E}_1^{int}(T_0)) \quad (S11)$$

in which  $C(R)$  is the non-uniform compression factor, reminiscent to the complex-logarithmic cortical magnification (see Ross et al., 1997, for details). Clearly, also this model predicts that the localization errors will scale with the primary saccade metrics and kinematics, but in addition also depend on the retinal eccentricity of the target probe. In this study, we have only looked at the former aspect of the model prediction. We have not attempted to find optimal fit parameters for the Ross et al. model to describe our data.

*Model predictions.*

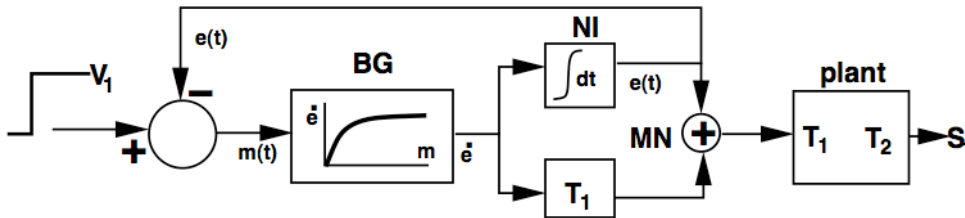
To demonstrate the predictions of the different models captured by Eqn. S10 a ‘real’ saccade was simulated by a simplified version of Robinson’s feedback model (Van Gisbergen et al., 1981). The internal eye position,  $e(t)$ , evoked by a step displacement in stimulus location,  $V_1$ , is described by (Fig. S1):

$$e(t) = m_0 \ln \frac{C \exp(v_0 t / m_0)}{1 + C \exp((v_0 t - V_1) / m_0)} \quad \text{with} \quad C \equiv \frac{1}{1 - \exp(-V_1 / m_0)} \quad (S12)$$

in which  $m_0$  and  $v_0$  describe the main sequence nonlinearity of the burst generator (BG):

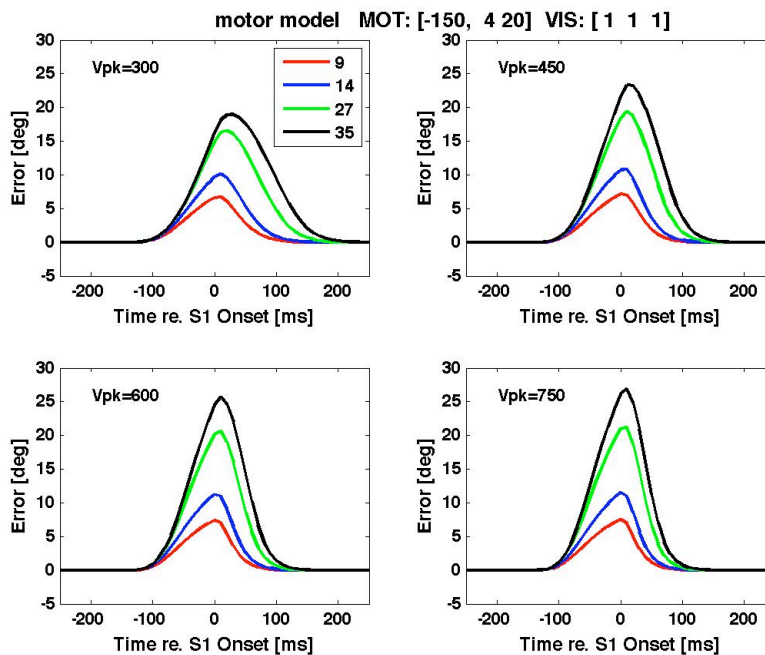
$$\dot{e}(t) = v_0 \cdot (1 - \exp(-m(t) / m_0)) \quad (S13)$$

and  $m(t)$  is the dynamic motor error:  $m(t) = V_1 - e(t)$  (see scheme).



**Fig. S1:** Simple version of Robinson’s internal feedback model. BG is the nonlinear burst generator, NI the neural integrator, MN the motoneurons. The plant is a second-order linear filter with time constants  $T_1 = 0.15$  s and  $T_2 = 0.012$  s.

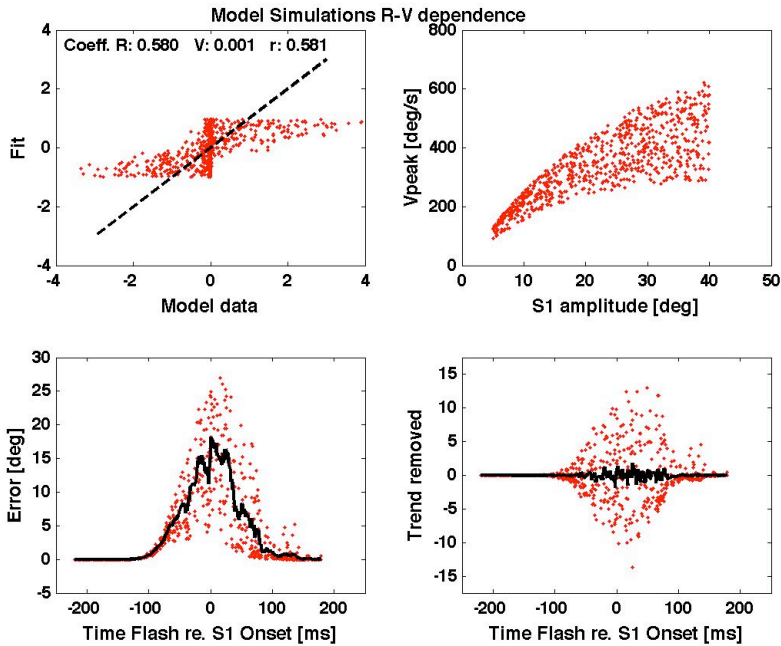
To generate a large number of saccades with varying amplitudes and kinematics, the characteristics of the BG were varied over a considerable range, while the model produced saccades between [5-40] deg. Then, for each saccade, the Dassonville proposal (Eqn. S3), as described in the Methods section was applied to compute the internal eye position signal for the target update. Then, the error was computed for various T0 delays (from -250 to +250 ms, in 10 ms steps). The same could be done for Pola's proposal (Eqn. S10), for given parameters of the visual filter. Fig. S2 shows an example of error patterns obtained for four different BG kinematics (indicated by the different  $v_{pk}$  values), and four different amplitudes (see legend) for Dassonville's model.



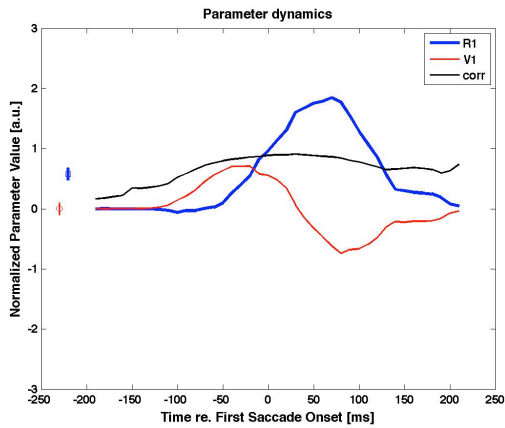
**Fig. S2:** Prediction of the perisaccadic error patterns for Dassonville's model ( $T_{lead}=150$  ms, order  $n_s=4$ , time constant  $T_s=20$  ms) for saccades of four different amplitudes and different BG kinematics. Note the influence of both saccade parameters.

Fig. S3 shows the results of multiple linear regression analysis on the residual errors of the model saccades. The top-right panel shows the main sequence properties of about 1000 simulated saccade responses, which were subjected to the Dassonville model (Eqn. S3). The lower-left panel shows the distribution of predicted localization errors as function of the flash delay, together with a running average. The lower-right panel shows the residual errors, after subtraction of the running average. Finally, the upper left panel shows the regression result over the entire population of saccades, taken over the entire [-250, +250] ms delay window. The partial correlation coefficient for amplitude is  $a=0.58$ , for mean eye velocity it is only  $b=0.001$ . Even the overall fit of the regression model is not particularly impressive ( $r=0.58$ ). As Fig. S4 clearly shows, the dynamic regression analysis is essential to extract the real influence of the different parameters.

These results are not very sensitive to the precise values of the model parameters. Essentially the same data can be generated for the model described by Eqn. S10.



**Fig. S3:** Properties of 1000 simulated saccades, subjected to the Dassonville model (same parameters as Fig. S2). Bottom panels show the perisaccadic localization errors, and residual errors. The top-left panel gives the result of the overall multiple linear regression analysis.



**Fig. S4:** Result of the dynamic regression analysis shows a strong modulation for both  $a(T_0)$  and  $b(T_0)$ , quite reminiscent to what was found for the real saccades in this study (Fig. 8). Note also the high correlation (black line) for the simulated data within the interesting epoch, which is roughly between -150 and +100 ms around saccade onset.