

## 1. Introduction

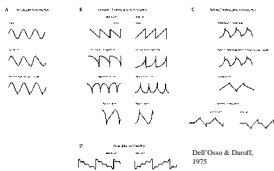
Congenital Nystagmus (CN) is a pathological involuntary oscillation of the eyes with an onset within the first few months of life. The incidence of CN is about 1:3000. CN is lifelong and there is no known treatment.

Unlike *acquired* nystagmus, CN is not caused by any known neurological abnormality. Instead, most cases of CN (>90%) are associated with a congenital visual disorder, which may be genetic (such as albinism) or neonatally acquired (such as corneal infection). In <10%, no known abnormality can be detected and the condition is labelled as 'congenital idiopathic nystagmus' (CIN).

Although there have been numerous models of how the oculomotor circuitry might generate CN waveforms, there has been no explanation why CN might develop in the first place. We propose, for the first time, a developmental model to explain how sensorimotor plasticity can result in permanently wobbling eyes.

## Waveforms

A unique feature of CN is that only a few waveforms are ever observed, and that many of these are not seen in acquired nystagmus. This phenomenon is helpful in diagnosis, but many investigators have also felt that understanding why these waveforms occur may provide an important clue into understanding CN.



Dell'Osso &amp; Daroff, 1975

## Abnormal Pathways vs. Sensory Defect

There has been no explanation for the emergence of CN secondary to early-onset visual disorders. Some have suggested that CN may be caused by abnormal patterns of decussation at the chiasm (as in albinism or achiasmia). However, this cannot explain the many associations with conditions with no abnormal pathways, or the neonatally acquired cases of CN.

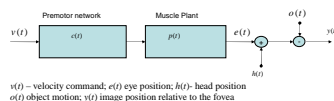
The more likely possibility is that CN reflects a post-natal developmental response to an abnormal sensory input (eg. foveal hypoplasia), at a time when the visual pathways are known to be highly plastic ('critical period'), and when oculomotor systems are also undergoing rapid development.

Could CN be an adaptive response ?

## 2. Controlling Retinal Image Position

Our key assumption is that fixation (gaze holding) and smooth pursuit systems are not hardwired or predetermined, but develop post-natally in response to the visual environment.

Specifically, we propose these eye movements develop to manipulate the position of the retinal image  $y(t)$  of an object to maximize visual contrast. For a normal developing foveate retina, this results in maintaining the image on the emerging fovea. This is accomplished by so-called 'normal' eye movements such as steady fixation and good smooth pursuit performance.



What would happen when the fovea does not develop (eg. foveal hypoplasia) or when the fovea cannot be used due to poor optics (cataract, myopia etc.) ?

## Velocity Bias

Psychophysics has demonstrated that sensitivity to a spatial frequency is maximal at some non-zero image speed, where the optimal speed varies inversely with spatial frequency. Thus, high spatial frequencies (as mediated via the central retina) require very low drift speeds, whereas low spatial frequencies require more moderate speeds to induce maximal visual contrast (Burr and Ross, 1982; Visu et al., 1982).

Therefore with diminished foveal functioning, we would expect not only lower acuity but also that visual contrast will be enhanced by some degree of image motion – a velocity bias,  $p$ . The conflict for the visual system is how to keep the image on the fovea (or its remnant) and to keep the image moving at the same time. What is the best strategy?

## Visual Performance Index (Cost)

We couch the question as a cost minimization problem. We propose that there is positional error cost that increases the further the image is away from the fovea, and a velocity costs when the image speed deviates from the optimum speed,  $p$ . Total cost over a visual integration period  $T$  is then:

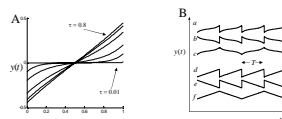
$$\text{Cost} = \int_0^T (\alpha [ax^2] + \beta [b(x-p)^2]) dt$$

## 3. The Optimal Trajectory

Using the calculus of variations, optimal trajectories are given by:

$$y = Ae^{-t/\tau} + Be^{t/\tau}$$

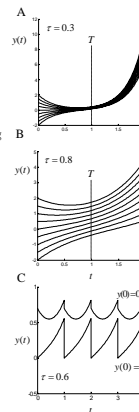
where  $\tau = \pm\sqrt{b/a}$  and  $A$  and  $B$  are determined by boundary conditions. The optimal trajectories require the image to move across the fovea with a net change in image position ( $A$ ). For extended viewing, therefore, the image must oscillate back and forth, which for a stationary object, can only be achieved by oscillatory eye movements ( $B$ ). Thus, perhaps counter-intuitively, nystagmus maximizes contrast!



## Oculomotor Constraints

In reality, the ideal waveforms could not be generated by an infant oculomotor system. In particular, resetting at the end of an epoch can only be achieved rapidly with saccades (fast phases). These leads to two constraints:

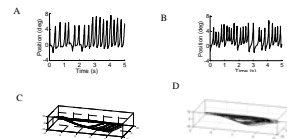
- 1) saccades are not perfectly accurate, so the oculomotor system cannot precisely determined the starting position of the next epoch. In this cases different trajectories become optimal depending on the starting position (A,B), leading to different waveforms (C) which are in agreement with observation
- 2) The timing of fast phases is quite stochastic (especially in an infants). This means that the optimal trajectory will become extended in time and because of the high accelerations will lead to large amplitude nystagmus, as observed



## 4. More Complex Predictions

### Dimensional Analysis

Abadi et al. (1997) performed a dimensional analysis of CN waveforms and found low dimensional fractional dimension of 1.41 (A & C). We simulated a sequence (B & D) and found similar fractional dimension (1.42). Thus our model captures this important feature of CN.



### Null Region

We can show that these ideal waveforms can only be generated at one gaze eccentricity. At other eccentricities, the waveform would have to increase in amplitude. This implies that a null region would be inevitable, and that a head turn would be preferred over off-null viewing.

## 5. Discussion

Most of the unique waveforms associated with CN can be considered to be local optimal solutions to minimising the visual performance index. The key assumption is that contrast to motion is maximised for a non-zero retinal slip,  $p$ . Thus waveforms are optimal compromises between minimising foveal eccentricity and maintain desired image speed.

We hypothesise that the desired non-zero  $p$  arises from the deficiency central retinal receptive fields. More peripheral retinal ganglion receptive fields, which now dominate the abnormal visual system, are maximally stimulated by much greater image motion than would be needed in the fovea. The developing and highly plastic oculomotor system attempts to maximise contrast, thus leading to CN.

**In conclusion we propose that CN is an adaptive process responding to abnormal sensory input at a time of heightened neural plasticity.**

### References

- Abadi, R.V., Broomhead, D.S., Clement, R.A., Whittle, J.P. & Worfolk, R. Dynamical systems analysis: a new method of analysing congenital nystagmus waveforms. *Exp. Brain Res.* 117: 355-361 (1997).  
 Burr, D.C. & Ross, J. Contrast sensitivity at high velocities. *Vision Res.* 22, 479-484 (1982).  
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 Visu, V., Rovamo, J., Lantinen, P. & Nalator, R. Temporal contrast sensitivity and cortical magnification. *Vision Res.* 22, 1211-1217 (1982).