Development of Coordinated Eye and Head Movements during Gaze Shifts

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Introduction

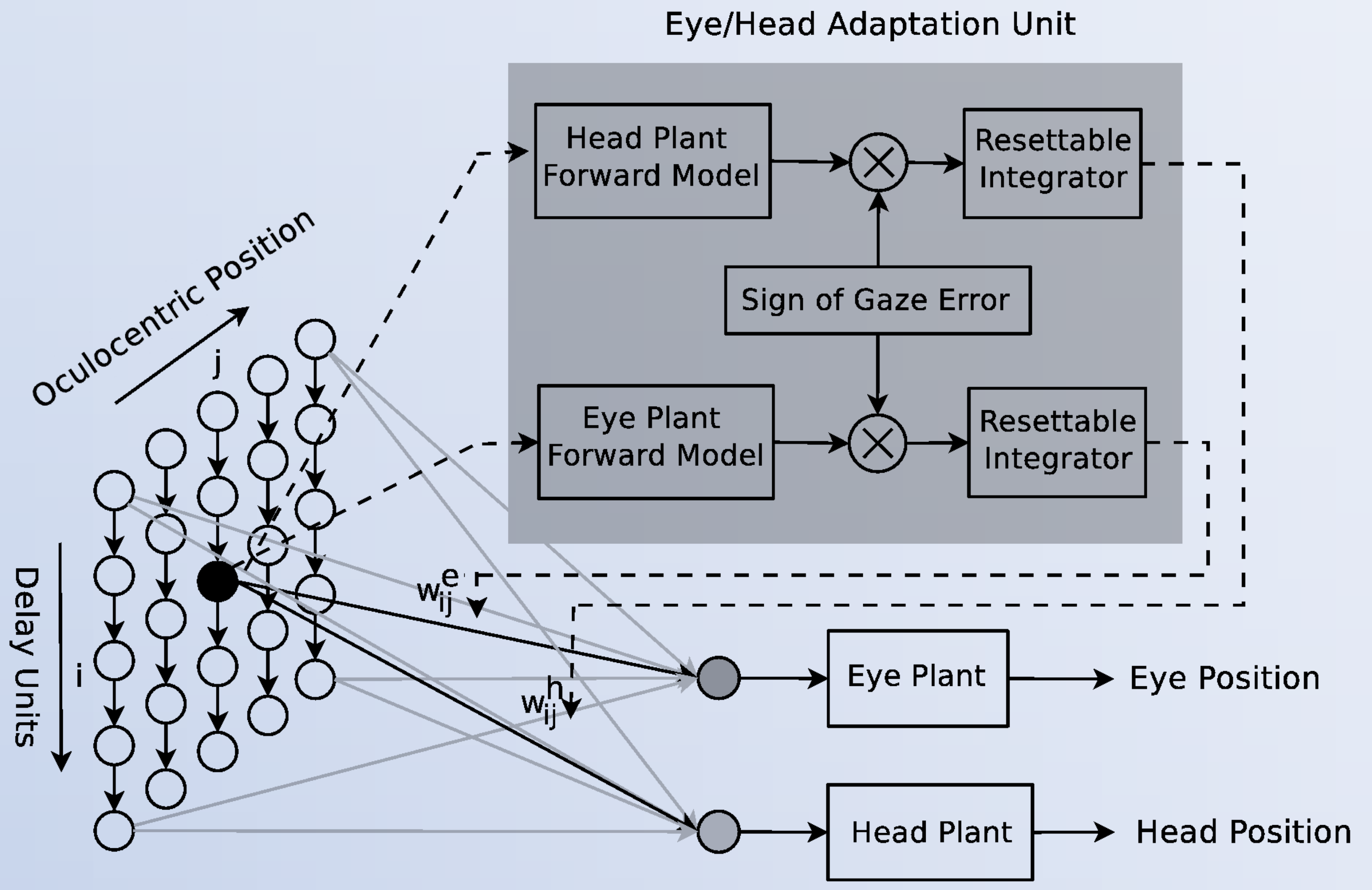
Saccades comprise multi-segment control of different motor systems, i.e. the coordinated movement of several parts of the body including the eyes and the head. Experimental studies have revealed that during saccades, the motor system follows certain characteristics such as respecting a specific relationship between the relative contribution of eye and head to total gaze shift.

Various optimality principles have been proposed to explain the stereotypical characteristics of coordinated eye and head movements [1,2]. However, the neural substrate of the underlying computations is usually left unspecified. At the same time, researchers have suggested several neural models to underly the generation of saccades, but these do not include online learning as a mechanism of optimization [3,4].

In this study, we suggest an open-loop neural architecture. We try to obtain an adaptation mechanism that on one hand can be implemented by the brain circuitry, and on the other hand minimizes a cost function. To this end, we propose a cost function that does not directly depend on saccadic duration as in previous studies, and therefore allows for a gradient descent based solution without any need to presume boudary conditions. The control pathway of our model is feedforward and is constantly calibrated by an adaptation mechanism. It can be regarded as a first step towards bringing together an optimality principle, a neural architecture, and a local adaptation mechanism into a unified control scheme for coordinated eye and head movements.

Model Architecture

Model architecture consists of several delay lines, two read-out neurons and the adaptaion unit, as shown in the following diagram.



- * When a saccade is initiated, a single delay line corresponding to the desired gaze shift amplitude is activated., which means a **Gaussian wave of activity** propagates through the neurons of that line starting from the first neuron.
- * Two **linear read-out neurons** integrate the activity of delay lines by means of weighted connections to form the neural command signals.
- * Eye and head are modeled as linear pole-only plants .

Adaptation

We propose a cost function that depends on the gaze error $r_g(t)$ and the absolute value of weight parameters:

$$E = \int_0^T |r_{\mathrm{g}}(t)| dt + \sum_{j=1}^{N} \sum_{i=1}^{M} (\alpha_{\mathrm{e}} |w_{ij}^{\mathrm{e}}|^n + \alpha_{\mathrm{h}} |w_{ij}^{\mathrm{h}}|^n)$$

T is an arbitrarily chosen period that is large enough to cover the saccade period.
The following adaptation rules are derived from the proposed cost function:

$$w_{ij}^{\mathrm{e}} \leftarrow w_{ij}^{\mathrm{e}} + \delta_{ij}^{\mathrm{e}} \int_0^T \mathrm{sign}(r_{\mathrm{g}}(t))\, \zeta_{ij}^{\mathrm{e}}(t)\, dt - 4\delta_{ij}^{\mathrm{e}} \alpha_{\mathrm{e}} (w_{ij}^{\mathrm{e}})^3$$

$$w_{ij}^{\mathrm{h}} \leftarrow w_{ij}^{\mathrm{h}} + \delta_{ij}^{\mathrm{h}} \int_0^T \mathrm{sign}(r_{\mathrm{g}}(t))\, \zeta_{ij}^{\mathrm{h}}(t)\, dt - 4\delta_{ij}^{\mathrm{h}} \alpha_{\mathrm{h}} (w_{ij}^{\mathrm{h}})^3$$

where:

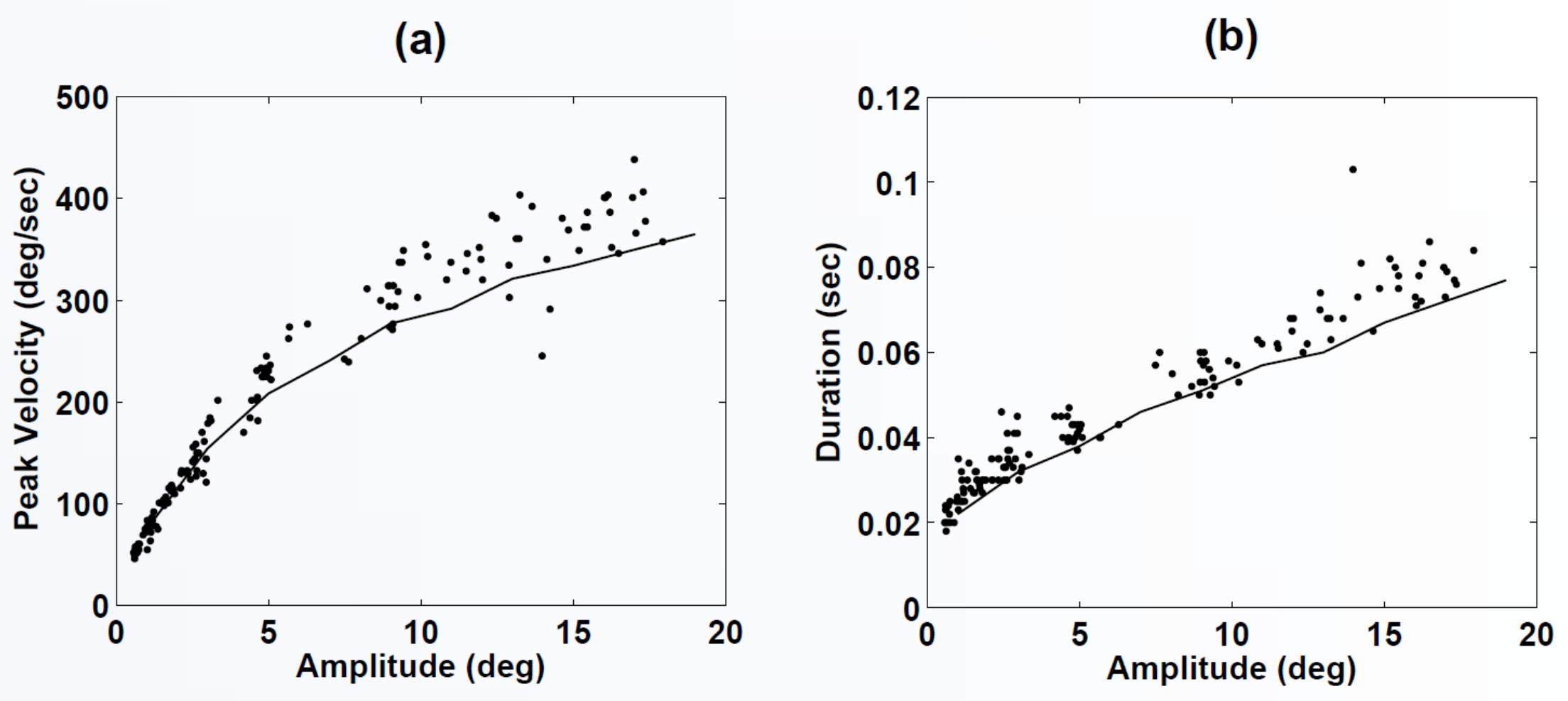
$$\zeta_{ij}^{\mathrm{e}}(t) = \int_0^t s_{ij}(\tau) h_{\mathrm{e}}(t-\tau) d\tau.$$

$$\zeta_{ij}^{\mathrm{h}}(t) = \int_0^t s_{ij}(\tau) h_{\mathrm{h}}(t-\tau) d\tau$$

- $h_e(t)$ and $h_h(t)$ are the impulse responses of eye and head plants, respectively;
- δ_{ij} is the learning rate;
- α_e and α_h are free parameters of the model, used to fit it to data.

Results

Figure 1. Comparing the main sequence plots of the model after learning (solid lines) to experimental data obtained by Harwood and colleagues [5].



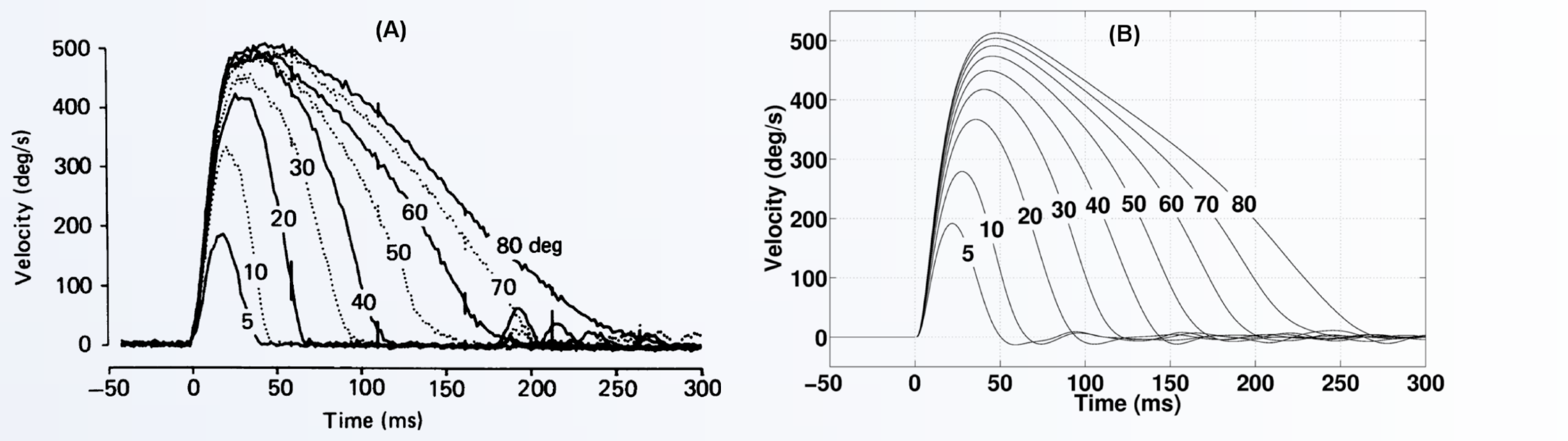


Figure 2. Comparing model velocity profiles (B) to experimental data (A) obtained by Collewijn and colleagues [6].

Figure 3. Eye (A) and head (B) contribution to total gaze shift vs. gaze shift amplitude. Dots show experimental data obtained by Freedman and Sparks [7], and green curves are model results.

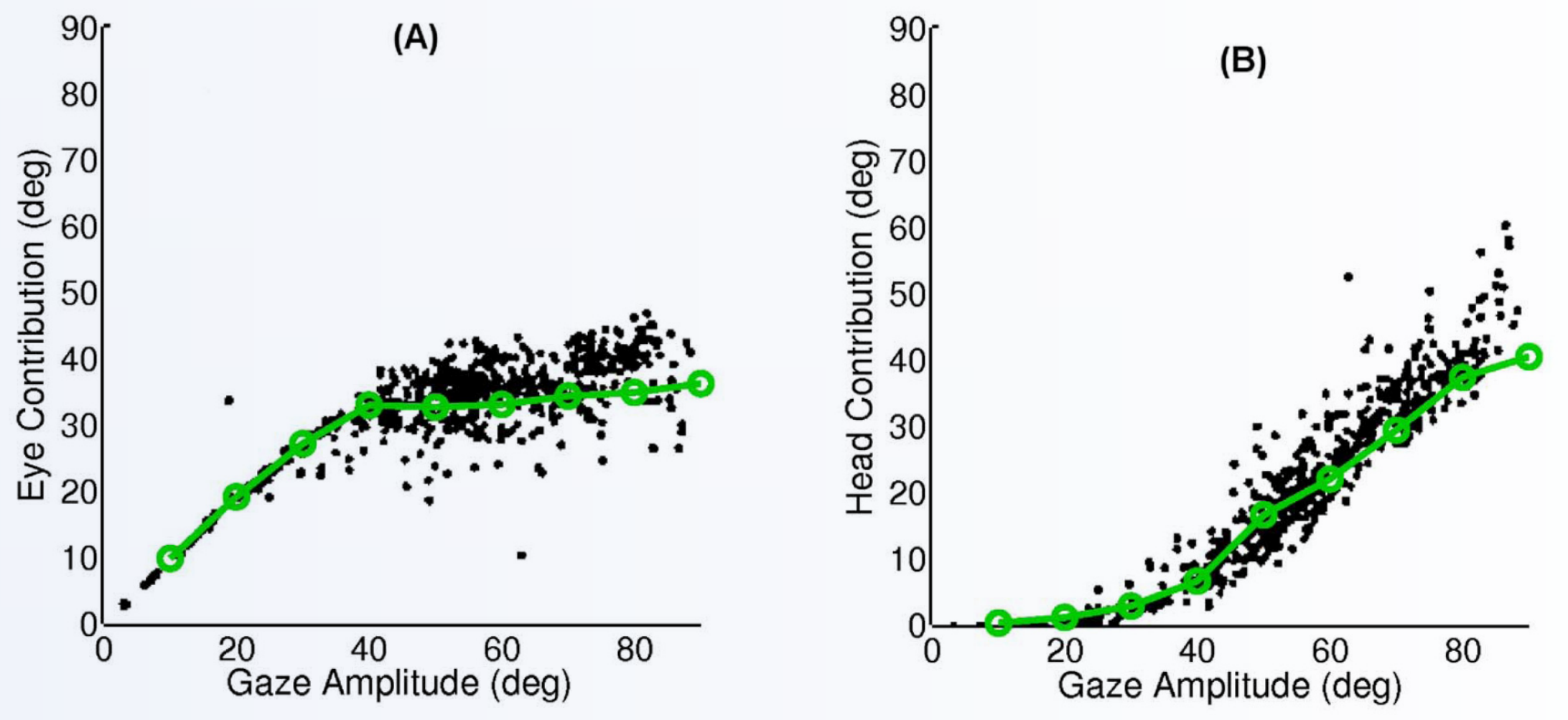


Figure 4. Variation of eye, head and gaze position over time for a 80 degree gaze shift. The model is also able to reproduce the beginning of the so-called vestibulo-ocular reflex phase, when the eye returns back to its central position in head while the head continues to move in order to stabilize the gaze.

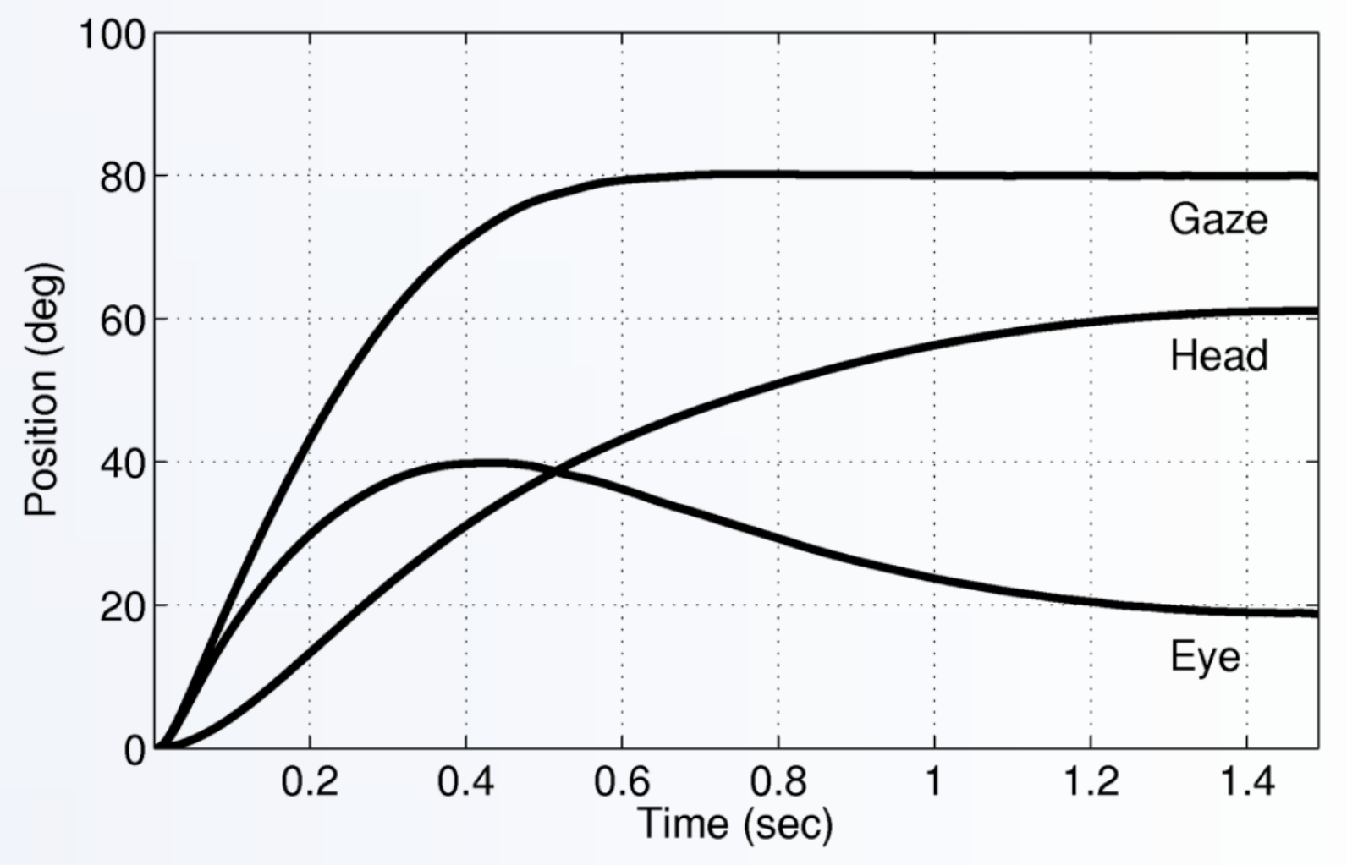
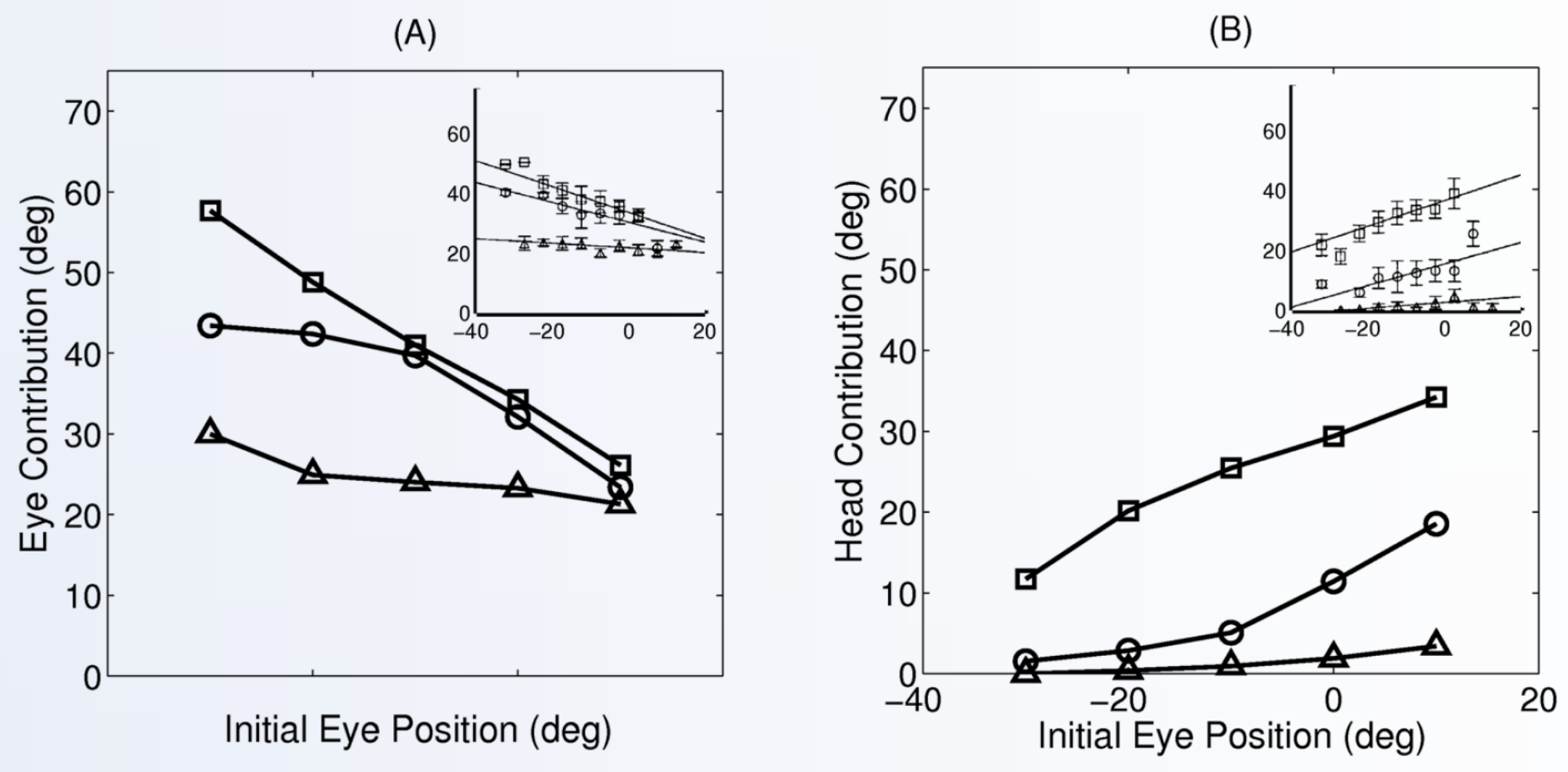


Figure 5. Eye (A) and head (B) contribution to the gaze shift as a function of initial eye position. Main plots are model results and insets show experimental data obtained by Freedman and Sparks [7].



Conclusion

Using the proposed architecture and cost function, we were able to reproduce the fundamental characteristics of coordinated eye and head movements in both head-restrained and head-free conditions. The proposed cost function does not directly penalize the gaze shift duration, thereby it allows for the application of the gradient descent method, whereas the previous principles do not. As a result, the adaptation mechanism can be implemented by brain circuitry.

Acknowledgement

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References

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