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Introduction

The oculomotor control system is usually modeled, in fixation and tracking tasks, as a unity negative feedback loop (Fig. 1); we call this internal loop "the primary visual feedback loop". This model does not explain however some eye tracking characteristics such as prediction phenomena in tracking a periodic target [2], step-ramp responses [3] or adaptive performance exhibited in large negative feedback experiments [4]. Furthermore, this simple automatic servo cannot account for eye tracking of non-visual stimuli and, clearly, analysis of more complicated tasks calls for models with higher level control [3].

Experiments implementing secondary visual feedback (2VFB) suggest [5,6] that the human controller can select one of two distinct strategies in executing a tracking or fixation task; in the first, there is a sensory dependent control aiming at error elimination, whereas in the second there is a switchover to higher level control. In the latter there is not necessarily elimination of an error, although here too the sensory signal can be utilized by the observer.

Primary Visual Feedback Models

In foveal lower level control mode of target tracking, the human observer utilizes a strategy of error elimination where the error $e = \theta_T - \theta_F$, θ_T and θ_F being the target and foveal angular positions. To account for a subject's ability to inhibit such reflexive response to target displacement, we modify the classical saccadic control model [1] by introducing a disconnect switch (Fig. 1) operated from a higher level.
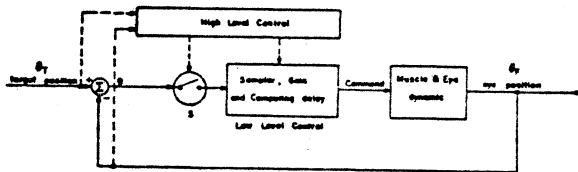

Fig. 1: Modified saccadic-control sampled data model incorporating a high-level controller, and a disconnect switch S representing a mechanism for suppression of reflexive responses.

This model can accommodate also responses in visual-stimuli dependent goals, in which there is no retinal position error elimination [7] or behaviour in tasks in which there is no visual or any other sensory stimulus; in these cases the system is driven by the high level controller.
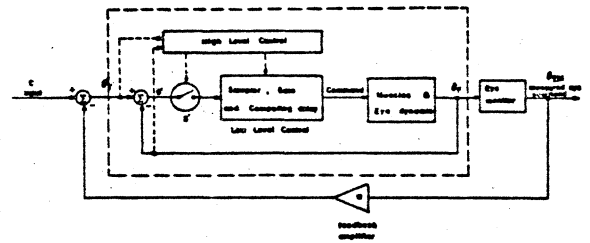

Fig. 2: Model for saccadic control in variable feedback experiments. The measured eye position signal θ_{EM} is amplified and summed up with the input C to initiate a response.

The same model, Fig. 2, is similarly modified to accommodate variable feedback experimental results [8]. In this case the error $e' = \theta_T^* - \theta_F$, where $\theta_T^* = c - \alpha\theta_{EM}$ and θ_{EM} denotes the measured eye position signal. Assuming $\theta_{EM} = \theta_F$, we obtain: $e' = c - (1+\alpha)\theta_F = c - K\theta_F$, where K is the overall negative feedback gain. Clearly, for $K > 2$ ($\alpha > 1$), any attempt to eliminate the error e' in the lower level controlled "reflexive-tracking" mode results in an underdamped oscillatory pattern of eye movements. The higher level controller provides adaptive gain enabling suppression of these oscillations [4].

Given an experimental condition of $K = 0$ ($\alpha = -1$), tracking in the lower level automatic control mode results in an open-loop response [8]. This, however, can be suppressed by trained subjects who disconnect the automatic feedback loop [5].

Secondary Visual Feedback Models

Displaying the point of gaze to the subject in addition to the target provides a secondary visual feedback [5] which is represented in the model by an external loop (Fig. 3). Under these circum-
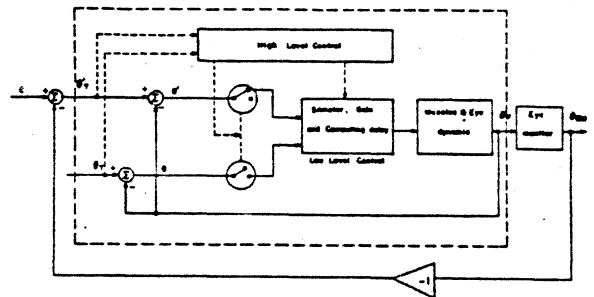

Fig. 3: Model for saccadic control in experiments implementing 2VFB. Subjects can select, as a control signal, one of the two possible errors.

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stances each of the two visual signals, viz. the target θ_T and the 2VFB signal, θ_T^i, can serve as a control signal. These signals affect two position errors: $e = \theta_T - \theta_F$ and $e' = c + \theta_{EM} - \theta_F = c$.

For experimental condition of c = 0, the 2VFB provides the subject with an extra artificial indication of his performance. This improves tracking only within a velocity range of approximately 1-10 deg/sec. The indication of error by the 2VFB feedback loop elicits corrective saccades. These intermittent saccades interfere with tracking as the target velocity increases until subject switches strategies ignoring the 2VFB signal.

The 2VFB signal can be shifted laterally by a fixed angle with respect to the point of gaze ($c \neq 0$) in which case the task still remains the superimposition of the two target points. Under this experimental condition, there is a third error (Fig. 4), $e'' = c + \theta_{EM} - \theta_T$. Subjects select one of the three possible error signals in controlling their eye movements depending on the required task, experience and preferred strategy.
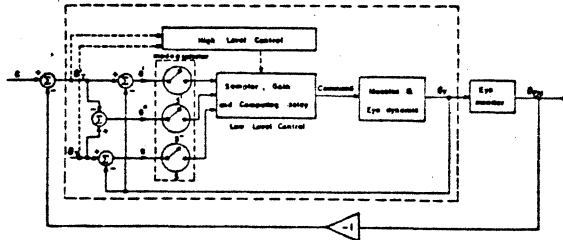

Fig. 4: Model for saccadic control in eccentric fixation and peripheral saccadic tasks. In addition to the two possible error signals indicated in Fig. 3, there is here a third error signal e" indicating the angular distance between the two point signals.

In eccentric fixation task, the error e" has to be eliminated, requiring: $\theta_F = \theta_T - c$ [5] This calls for reversal of response direction with respect to the 2VFB signal which is not an automatic - "preprogrammed" - mode of response, and thus an untrained subject selects at first a strategy attempting to eliminate e'. Obviously, since the 2VFB signal is locked on the retina, the error e' can not be eliminated and this attempt results in a staircase pattern of eye movements characteristic of the open-loop mode Training affects a switch-over to the required error signal, e", already within the first session, but, since both signals fall off the fovea, subjects lose their eccentric fixation and return to the stable state of foveal fixation. Fully trained subjects can maintain eccentric fixation as long as there is no external disturbance. If however target or 2VFB signals are changed abruptly, during eccentric fixation, the automatic response of foveal fixation takes over again. This suggests that when a task calls for multiple or varying higher level control func-

tions the system automatically reverts briefly to the simplest task - target foveation.

Another possible manipulation of the 2VFB is a change in the gain to $\alpha < -1$, in order to amplify the fixation position error, (c = 0 is retained). Due to dual target information load, fixation performance declines [5]. As the fixation error is further amplified so that for errors smaller than the size of the fovea, the 2VFB falls off the fovea, any attempt to eliminate e" results in instability and subjects switch back to control by means of the internal loop, disregarding the 2VFB.

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SUMMARY

Displaying the point of gaze in addition to the point-target provides a secondary visual feedback (2VFB). Experiments implementing 2VFB conditioned by dc shift or change in gain suggest that the human controller selects one of three possible position errors as control signal, or switches over to employ a strategy where there is no error elimination. A sequence of models accounting for variable feedback and 2VFB experimental results is presented. In the first, the saccadic-control sampled data model is modified, incorporating high-level controller and a disconnect switch to accommodate non-automatic modes of operation. The same modification is introduced also in the specific model for variable feedback experiments to accommodate adaptive responses exhibited when large negative feedback is imposed. Both models are combined into a double-input single-output model of eye movement control in 2VFB experiments. A third position error which can be selected by the observer in eccentric fixation tasks is incorporated in the fourth model.