SHORT-TERM ADAPTATION IN DISPARITY VERGENCE EYE-MOVEMENTS

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ABSTRACT

The high-velocity initial component of disparity vergence eye movements is modified by stimuli that generate large transient disparities. Modification was observed in all three subjects studied. After modification, the peak velocities were substantially higher than in normal baseline responses. The temporal distribution of the peak velocities for a step stimulus as a function of number of trial revealed the existence of a very rapid adaptive process in the vergence system. Plots of main sequence, however, showed that the first-order dynamic characteristics of all initial components were the same for both pre- and post adaptive responses. A process of recovery or de-adaptation was also observed.

INTRODUCTION

Adaptation may be one of the most important characteristics for the survival of a species. Adaptive processes can be found in nearly every major physiological system. Motor systems, for example, must rely on adaptive processes to ensure continuing precision in the face of changes in muscle efficiencies and mechanical properties [1]. In many of these systems, open-loop operation modified by adaptive processes represents the paradigm control strategy. In this paradigm, feedback information, rather than modifying an ongoing response, drives adaptive processes that provide compensation over the long-term.

The Dual-Mode [2] describes the dynamic properties of vergence eye movements using a two-component control system. The initial component is a preprogrammed, open-loop control process, that is activated by rapidly moving targets. The slow component is mediated by a feedback control system and tracks slowly moving targets, as well as corrects for post initial component vergence errors [3]. If the initial component is open-loop, an adaptive modification of the underlying control processes, driven by some form of error information, might be expected.

In the saccadic system, short-term adaptive processes have been clearly identified and well studied [4],[5],[6]. These adaptive processes were activated by forced postsaccadic error induced by specially developed training stimuli. The adaptation developed progressively, increasing or decreasing the saccadic response amplitude depending on the nature of the training stimulus. Given the similarity between the general neural organization controlling vergence and saccadic eye movements [7], adaptation should also be expected in the vergence system. The experimental evidence presented here confirms the existence of short-term adaptation in disparity vergence eye-movements.

METHODS

Experiments were designed to record horizontal symmetric vergence eye movements of both eyes in response to two different visual stimulus patterns: a training stimulus and a test stimulus. The training stimulus consisted of a step-ramp pattern: an initial step presented in conjunction with constant velocity stimulus, i.e. a ramp (Figure 1A). This stimulus was designed to induce large dynamic errors and is defined in terms of the amplitude of the step and the slope of the ramp. The test stimulus was used to monitor the modifications induced by the training stimulus and consisted on a standard step, defined by its amplitude (Figure 1B).

A protocol was designed to provide repeated exposure to the training (or adapting) stimulus while minimizing prediction, particularly for the test stimuli. A typical experimental run was composed of four sections or modes: a pre-adapt mode, an adapt mode, a sustain mode and a recovery mode. The pre-adapt mode consisted of at least 10 sequential test stimuli of the same amplitude. Though the amplitudes of the sequential stimuli were predictable, onset time was randomized (between 0.5 to 2 sec). The purpose of the pre-adapt mode was to
establish the baseline behavior of the vergence response. The *adapt* mode consisted of training and test stimuli randomly intermixed at an overall ratio of 5 training to one test stimulus. Again, onset time was randomized. The *adapt* mode continued until at least 50 training (and 10 test) stimuli had been presented. The *sustain* mode consisted of randomly intermixed training and test stimuli at a 3 to 1 ratio, and continued for at least 21 training (and 7 test) stimuli. This mode provided for a greater number of test stimuli for later analysis. Finally, the *recovery* mode consisted of test stimuli only and was used to study the return adaptation of processes to pre-test levels.

The stimulus target consisted of two stereoscopically-paired vertical lines (0.2 deg. in width and 8 deg. in height) presented on a pair of oscilloscopes (phosphor P31 with a bandwidth of 20 MHz) arranged as a haploscope. To minimize motion artifact and avoid the influence from the vestibular system, the subject’s head position was fixed in a dental impression bite bar. Only the target was visible to the subjects. Two real-world targets provided well established reference points that were used to calibrate the stimulus device. Proximal influences related to changes in target disparity were minimal in the device, due to a lack of depth information related to the target [8].

The vergence eye movement responses were monitored using a limbus tracking system (Skalor Iris 6500). The eye movement monitor has a linearity of ±25 deg with a resolution of 1.5 minutes of arc, and all movements were within the linear range. Left and right eye movements were recorded and calibrated separately, and then digitized using a standard 12 bit analog-to-digital converter. Calibration was carried out by recording eye movement monitor output at two known eye positions, immediately before and after each trial. Calibrations were stored and used to construct a separate calibration curve for each eye. Data acquisition was done at a sampling rate of 200 Hz, which is well above the Nyquist frequency for vergence eye movements.

Each stimulus, whether training or test, had a 2 sec duration. Several runs were presented on different days and inexperienced subjects received some initial training. Three subjects participated in this study. Each subject had normal binocular vision. One of the subjects, JS, was experienced and was aware of the goals of this study, while the others were inexperienced and naive to the study’s objectives.

The data analysis begun with the subtraction of left and right eye movements to yield the net vergence response. Any artifactual responses were omitted. However, since binocular behavior was the main concern, responses with small saccades were not necessarily discarded, as long as the saccades in two eyes canceled and occurred after the initial transient portion of the response. The velocity of each movement was computed using the two-point central difference algorithm [9]. The dynamic characteristics of the eye movements were examined using the Main Sequence analysis, which provides a quantitative description of the equivalent first-order dynamics of a movement.

**RESULTS**

Modification occurs rapidly and manifests an overshoot of 46 % in the response to test stimuli (a *step*) after a small number of adaptive trials (approximately 5 trials). Figure 2 shows the vergence amplitudes (Figure 2A) and velocities (Figure 2B) of a test response before and after adaptation.

**Figure 2A:** Position trace of a single vergence response before and after adaptation to an stimulus like in Figure 1B. Subject JS.

**Figure 2B:** Velocity trace of a single vergence response before and after adaptation to an stimulus like in Figure 1B. Subject JS.

The evolution of the adaptation process can be observed in Figure 3, where the peak velocity of each response is plotted as function of the trial number. This figure reveals a relatively constant peak velocity during the pre-adapt mode, corresponding to the average peak velocity in this subject for a step stimulus of 4 deg (14.5 deg/sec). During the adapt mode, the peak velocity showed a progressive increase, resulting from the short-term adaptation process. After 10 trials the maximal peak velocity was generally observed. As stated previously,
the sustain mode was included to maintain adaptive modification and provide more examples of adaptive responses for dynamic analysis. For Subject JS, the average peak velocity in sustain mode was 26 deg/sec. Finally, in the recovery mode (after trial 60), a return to the initial state of the system is seen. The recovery process was found to be faster than the adaptation process, with full recovery after only approximately 5 consecutive test stimulus.

Equivalent results were observed in the inexperienced subjects. The results for one of the subjects are shown in figures 5 and 6.

To study the dynamics of the vergence system under adaptive modification, the Main Sequence [10] was calculated for all responses and plotted in Figure 4. This plot reveals no apparent change in the dynamics of adapted responses, as evidenced by a relatively consistent peak velocity to response amplitude ratio of the order of 6 to 1 for Subject JS.

The results confirm the ability of stimuli that generate large dynamic vergence errors to produce short-term adaptive modification of vergence response amplitude. The modifications are quickly attained and short lasting. The rapid changes in behavior suggest that motor learning and not a true adaptive process may be involved. However, the fact that the adapting and test stimuli are quite different, and the existence of a definitive, though brief, after effect argue for true adaptation.
The first-order dynamics of the movements did not show an evident change, as connoted by the relatively constant peak velocity to response amplitude ratio. This indicates that the adaptive modification is mediated primarily as a gain change or a change in the effective stimulus.

The adaptive process studied here was anticipated by the Dual-Mode theory for the control of vergence eye movements. Under this theory, two components, a programmed initial component and a feedback controlled slow component guide vergence responses. In addition to correction for initial component errors (expected from an open-loop system), the slow component may modify the performance of the initial component, by providing corrective information from post-initial component vergence errors. In this scenario, the closed-loop system with its longer time constants adjust the fast, open-loop response to minimize error based on previous error information.

Although the stimuli employed demand some experience from the subjects to follow the target, in non-experienced subjects adaptation processes were also evidenced with similar performance as that obtained from the experienced subject. Therefore, adaptation appears to be an intrinsic characteristic of the disparity vergence control system.

CONCLUSION

This study confirms the expectations of an adaptive process in the initial control component of the vergence system. The step-ramp training stimulus provides a useful tool for generating the short-term adaptation of vergence amplitude. With this adapting stimulus, the adaptation process produces a substantial increase in response amplitude in a very short time period. Recovery processes were also observed that were even faster than the adaptive processes. The Main Sequence analysis reveals no appreciable change in the first-order dynamics properties of the vergence system, indicating that the adaptation is mediated primarily as a change in gain.

REFERENCES