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A Dual-Mode Dynamic Model of the Human Accommodation System

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The function of the accommodation system is to provide a clear retinal image of objects in the visual scene. The system was previously thought to be under simple continuous (i.e., single mode of operation) feedback control, but recent research has shown that it is under discontinuous (i.e., two stimulus-dependent modes of operation) feedback control by means of fast and slow processes. A model using MATLAB/SIMULINK was developed to simulate this dual-mode behavior. It consists of fast and slow components in a feedback loop. The fast component responds to step target disparity with an open-loop movement to nearly reach the desired level, and then the slow component uses closed-loop feedback to reduce the residual error to an acceptable small level. For slow ramps, the slow component provides smooth tracking of the stimulus, whereas for fast ramps, the fast component provides accurate staircase-like step responses. Simulation of this model using a variety of stimuli, including pulse, step, ramp, and sinusoid, showed good agreement with experimental results. Thus, this represents the first dynamic model of accommodation that can accurately simulate the complex dual-mode behavior seen experimentally. The biological significance of this model is that it can be used to quantitatively analyze clinical deficits such as amblyopia and accommodative insufficiency.

1. INTRODUCTION

The normal focusing of the human eye is achieved using a control process in which retinal image defocus is sensed and the ciliary muscle/lens is stimulated

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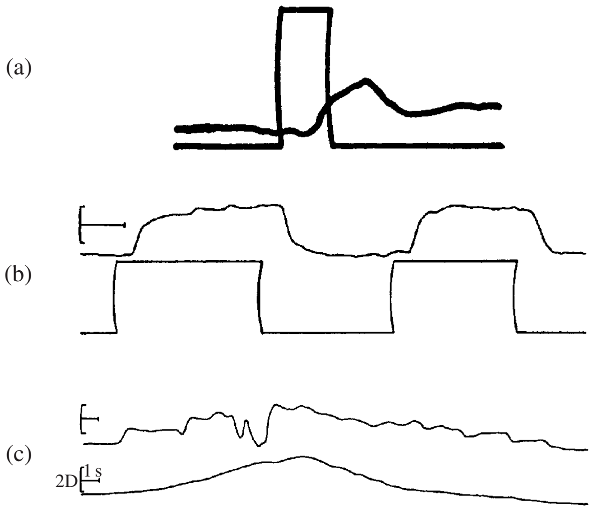

Figure 1. Experimental accommodative responses to: (a) 2D pulse stimulus of 0.32 s duration; (b) 2D step and return to zero level of accommodation stimulus. Marker length: horizontal—1 s; vertical—1 D; (c) gradually-changing stimulus, similar to an up- and then down-ramp stimulus. Note the irregular bumpy responses to the smoothly changing ramp stimulus. For (a)–(c), response on top and stimulus on bottom. Reprinted with permission from Campbell and Westheimer (1960) with the permission of The Physiological Society.

to provide a clear retinal image of the object (Campbell and Westheimer, 1960). Thus, the accommodation system can be thought of as a negative feedback control system in which the error is the retinal image defocus, the brain is the controller, and the ciliary muscle/lens is the system plant (Hung, 1998a,b).

The accommodation system responds to a variety of retinal-defocus stimuli, including pulse, step, ramp and sinusoidal inputs. For unpredictable stimuli, the accommodation system exhibits an average latency of about 370 ms, whereas for predictable stimuli, the delay decreases and can even be negative. This demonstrates the presence of anticipation, or a prediction operator, in the accommodation control system (Campbell and Westheimer, 1960). Accommodative responses to pulse, step, and ramp stimuli are presented in [Fig. 1(a)–(c)], respectively (Campbell and Westheimer, 1960). The pulse response [Fig. 1(a)] follows the pulse stimulus after a delay, and it has a duration approximately equal to that of the stimulus. This has been cited as evidence for continuous processing in the accommodation system (Campbell and Westheimer, 1960). However, a noncontinuous process that responds to rapid changes in the stimulus could also account for the accommodative behavior (Hung *et al.*, 1986; Khosroyani, 2000). The step response [Fig. 1(b)] typically exhibits a latency of 350–400 ms and an exponential rise with a time constant of about 250 ms (Campbell and Westheimer, 1960; Stark *et al.*, 1965; Krishnan and Stark, 1975; Tucker and Charman, 1979). The ramp response [Fig. 1(c)] shows small wavering movements both for its rising and falling portions. A more systematic study using ramp stimuli of various velocities

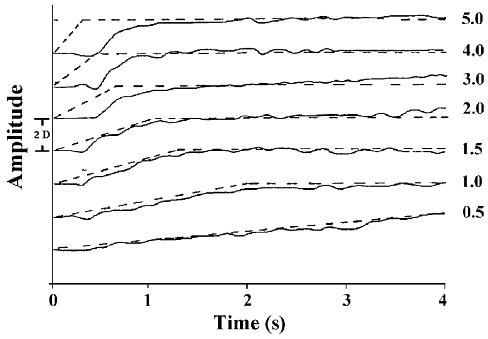

Figure 2. Experimental accommodative responses (solid) to different ramp stimuli (dashed) with velocities (shown at right of curve) ranging from 0.5 to 5.0 D/s. Maximum stimulus amplitude is 2D. Subj. GH. Note the multiple-steps in the responses to 1.0, 1.5 and 2.0 D/s ramps, and progressive shift from step-ramp to step responses for the 3.0, 4.0 and 5.0 D/s ramp stimuli. Reprinted from Hung and Ciuffreda (1988) with the permission of Elsevier Science Ltd.

(Hung and Ciuffreda, 1988, Fig. 2) found dynamic characteristics that were contingent upon the stimulus ramp velocity. For relatively slow ramps (0.5 D/s), the responses followed the target reasonably well. On the other hand, for intermediate velocities (1 to 2 D/s), the responses consisted of multiple-step movements in which the end of the step approximately coincided with the instantaneous position of the target. Further, for higher velocities ($\geq$3 D/s), the responses consisted primarily of steps and step-ramps. These results indicate that the accommodation system behaved differently based on the target velocity, and furthermore suggest a two-part or dual-mode control process consisting of fast open-loop and slow closed-loop components. Sinusoidal responses to stimuli of various temporal frequencies (Fig. 3) exhibit a decrease in response amplitude and an increase in phase lag with increasing stimulus frequency (Fujii *et al.*, 1970; Kasai *et al.*, 1971).

Various models have been developed based on this control system concept. In this paper, we have reviewed these models and compared the model simulations with known experimental responses, and have found noted discrepancies between these model simulations and experimental responses. Thus, we introduced a new dual-mode dynamic model for the accommodation system, and showed simulations that were in good agreement with experimental responses.

2. Accommodative Responses

Early models of the accommodation system had some success in describing its behavior. Toates (1972) developed a model with a proportional controller in the forward loop. It could account for the static steady-state error between the stimulus and response, but could not account for the dynamic behavior of the system. On the other hand, O'Neill (1969) developed a model with an integral controller in the for-

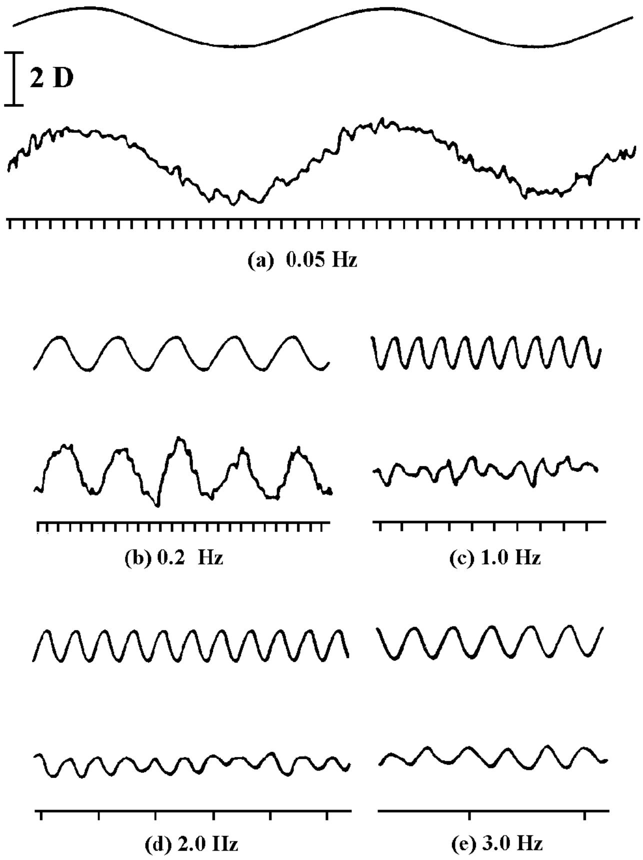

Figure 3. Experimental accommodative responses to sinusoidal stimuli at various temporal frequencies. In each case, the upper record shows the stimulus change, the middle trace the corresponding response, and the bottom line is marked in seconds. Reprinted from Kasai *et al.* (1971) with the permission of T. Kasai, the copyright holder.

ward loop, which could account for some of the dynamic but not the static behavior of the system (Jiang, 2000). Stark *et al.* (1965) derived an analytical model based on experimental data, which resulted in a rather complex transfer function in the forward loop. Their model simulations provided a good fit to the experimental data, but it required a time delay of 0.1 s, which was much smaller than the actual latency. Brodkey and Stark (1967) developed a model with a piecewise linear element and a transfer function having a 0.3 s latency in the forward loop. However, the phase lag of their model simulations did not match the experimental results. Krishnan and Stark (1975) attempted to resolve the proportional/integral controller dilemma by proposing the inclusion of a 'leaky' integrator element. The leaky integrator has the form $K/(\tau s + 1)$. It behaves as an integrator initially, but over long time periods it will exhibit first-order lag characteristics. Their model was able to simulate the observed decay of accommodation, lasting approximately 6 s, to the resting state when all stimuli are removed, but it gave a relatively poor representation of dynamic behavior (Krishnan and Stark, 1975; Eadie and Carline, 1995). Sun and Stark (1990) developed a switching control model for describing the accommodation response to ramp stimuli and microfluctuations. Their model simulations showed some reasonable results but they had to use an unrealistic 100 ms latency to achieve this.

The lack of success in modeling the accommodation system as a continuous feedback control system is not surprising. This is because the latency is considerably longer than the time constant of the response, so that the output, which responded to an input 370 ms earlier, is combined with the present input. This can lead to inappropriate responses and potential instability oscillations. Thus, the long response latency is a primary reason for the failures of the continuous model (Hung *et al*., 1986).

An indication as to the possible resolution of this modeling difficulty was provided by the results of an investigation of the human disparity vergence eye movement system (Hung *et al*., 1986; Semmlow *et al*., 1986). They presented ramp changes in vergence demand at different velocities in normal subjects. They found that for ramp velocities less than about 2 deg/s, the vergence system tracked smoothly. Also, for ramp velocities greater than 9 deg/s, the responses were steps. However for intermediate ramp velocities in the range of 2–9 deg/s, the vergence system tracked with step-ramp and multiple-step responses. The steps in the step-ramp responses were not simply continuously delayed movements reflecting an earlier disparity error, but were accurate step movements that matched the instantaneous ramp stimulus amplitude. These results suggested a preprogramming process in which the amplitude of the initial step was proportional to target velocity and equal to the predicted stimulus amplitude. At the end of the step movement, a slow continuous feedback controller then took over to adjust the vergence response until it was within a small acceptable error limit (Hung and Ciuffreda, 1988). Based on these results, Hung and others (Hung *et al*., 1986; Hung, 1998a) developed a dual-mode dynamic model for the vergence eye movement system. The simulation results of this model were in good agreement with experimental eye movement responses (Hung *et al*., 1986; Hung, 1998a).

Subsequently, Hung and Ciuffreda (1988) designed an experiment to examine whether dual-mode behavior may also be presented in the human accommodation system. They stimulated the accommodation system using different velocity ramp stimuli in the range of 0.5–5 D/s, and found that for ramp stimuli below 2.5 D/s, the response was smooth, whereas for stimuli above this level, step-ramp and staircase-like multi-step responses were elicited (Hung and Ciuffreda, 1988). These results were similar to those found earlier for the disparity vergence eye movement system (Semmlow *et al*., 1986). Thus, Hung and Ciuffreda (1988) concluded that the accommodation system also exhibited dual-mode behavior, and could be represented in the accommodation model by fast and slow components. The fast component provides the initial open-loop preprogrammed movement, which accounts for the relatively rapid rise in a step response, but without the instability associated with the long latency in a feedback system response. The slow component provides the subsequent closed-loop movement in the step response, which accounts for the relatively stable and accurate steady-state focusing of the eyes. The stimulus regimes (or range of displacements and velocities of optical power) for the fast and slow components are mutually exclusive, so that when one is activated, the other is inactivated. These two distinct regimes of operation result in discontinuous behavior. Moreover, the closeness of the boundaries between fast and slow component stimulus regimes, along with subsequent lowpass filtering by the accommodation plant (ciliary muscle and lens), ensures relatively smooth responses despite the transitions between the two components' responses. Since the accommodative response is relatively slow, the final response may appear continuous; yet the response shape could only have been generated discontinuously by two different components operating over different stimulus regimes.

The reader may request a MATLAB/SIMULINK version of the accommodation model presented herein from the corresponding author (George K. Hung at e-mail address shoane@rci.rutgers.edu).

3. MODEL

To quantitatively analyze the accommodative control system, a dynamic model was constructed based on the dual-mode model developed previously for the vergence system (Hung, 1998a). This was possible because the basic components of the two systems were similar, and only the parameter values needed to be changed to simulate the accommodation system. Selected model parameters and their values are shown in Table 1. Simulations of the accommodation model were performed for various parameter values for pulse, ramp, square- and sine-wave stimuli on a PC containing Matlab 4.2.c and Simulink 1.3.c. In the initial simulation process, the parameters were first set at approximately the middle of the range of possible values [e.g., threshold ranges found experimentally (Campbell and Westheimer, 1960; Hung, 1998b)] to provide initial simulation responses. Then, the parameters were fine-tuned to provide appropriate responses to all the different stimulus conditions used. Following the simulations, the results were plotted on a HP Laser Jet 5L printer.

4. RESULTS

4.1. ***Model configuration.*** The overall block diagram of the model is shown in Fig. 4(a). The first block is a deadspace operator, which represents the depth of field, with limits equal to ± 0.15 D. The controller consists of fast and slow components (Hung, 1998a). The fast component input is equal to the sum of the error signal and the efference copy signal from the fast component output. The efference copy signal takes into account the plant dynamics (Gilmartin and Hogan,

Table 1. Selected model parameter values.

Parameter	Value	Description
Athrsh	2500	Acceleration threshold (D/s) per degree for trigger of fast component for pulse and step.
Pcross	0.05 or 0.20	Percentage of period for maintenance of periodicity of cross-correlation between stimulus and response, for low and high velocity, respectively.
Pthrsh	0.75	Amplitude threshold (D) for trigger of fast component for ramp and sine.
Samptime	0.34 or 0.50	Sampling interval (s) of zero-order hold element for high and low stimulus velocities, respectively.
Tflag	0 or 1	Global flag for trigger of fast component and disable of slow component, and vice versa.
Thrsh1	0.25 or 0.45	Threshold for initial detection of peak of autocorrelation, for low and high velocities, respectively.
Thrsh2	0.15 or 0.40	Threshold for detection of maintained peak of autocorrelation, for low and high velocities, respectively.
Vthrsh	1.5	Velocity threshold (D/s) for trigger of fast component for ramp and sine.

1985). The combined effect results in an effectively open-loop fast component signal that is nearly equal to the original stimulus amplitude. This open-loop drive is important because it maintains stability in the presence of a relatively long latency (370 ms) and the requirement of an accurate step response. In contrast, such accuracy would correspond to very high gain in a continuous feedback control system, which would have resulted in instability oscillations.

The fast component output is an open-loop movement which accounts for most of the step response amplitude, with the remainder being taken up by the closed-loop slow component. The block diagram of the fast component is shown in Fig. 4(b). It is driven by a signal that represents the perceived target displacement. This is delayed by element 'DELAY2', which represents the effective delay throughout the fast component. The sampler and predictor act in conjunction to provide the sampling and predictive capabilities seen in the experimental ramp and sinusoidal responses. The sampler has a sensory threshold to account for the range of stimuli that elicit experimental sampling behavior. The sampler is triggered by a change in velocity of the perceived target above a given threshold. However, the sampler can be reset by a sudden change in target velocity, such as in a pulse stimulus. If the target velocity drops below a certain value, as in a step stimulus, the sampler is stopped. The sampler provides the sampling timing control for the predictor. The predictor is a calculating unit, which uses the target position and velocity information to estimate the future position of the target. The predictor estimates, within

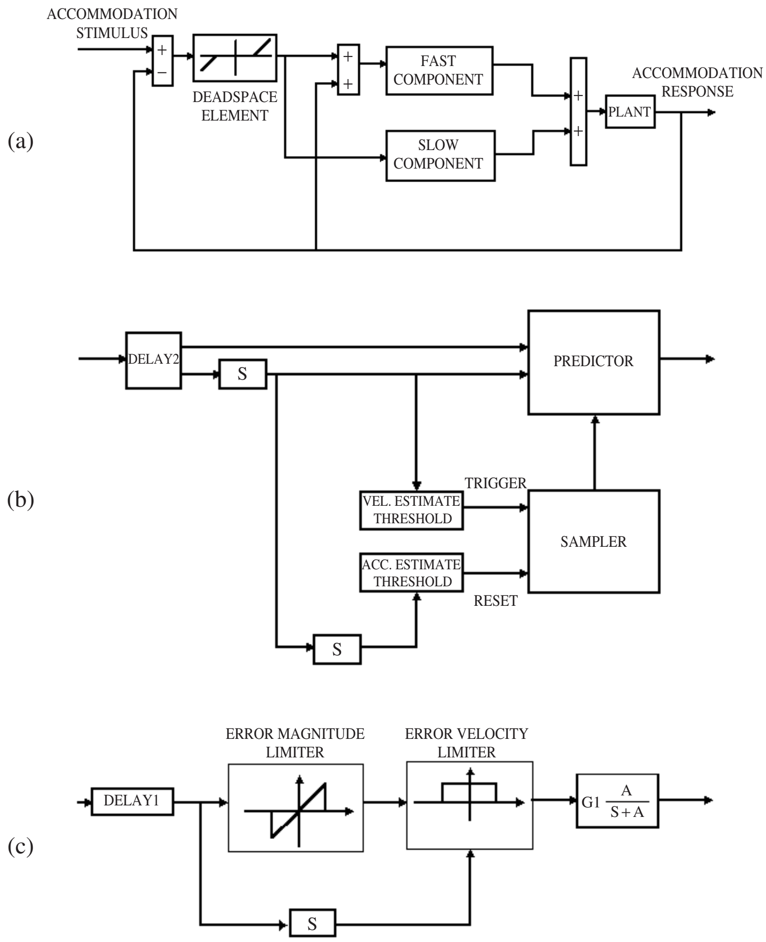

Figure 4. (a) Block diagram of the accommodation system used in MATLAB/SIMULINK simulations. The difference between accommodative stimulus and response, or accommodative error, is input to a deadspace element (thresholds at ±0.15 D), whose output is summed with the efference copy signal, resulting in a signal equal to the actual stimulus. This signal is used to drive the fast component. The output of the deadspace element also drives the slow component. The outputs of the slow and fast components are summed to drive the plant. The output of the plant provides the accommodative response. It is fed back and is subtracted from the accommodation stimulus to provide the error signal to the deadspace element; (b) the fast component operates in an open-loop manner, and it uses a sampler and has predictive capability for periodic stimuli; (c) the slow component operates under the closed-loop condition over a smaller range of accommodative error amplitudes and velocities. Latency = 0.37 s, gain G1 = 12, and time constant = 1/A = 10 s. The summed output of the fast and slow components drives the plant (time constant = 0.3 s). Overall, the fast and slow components operate over different stimulus regimes, so that when one is active, the other is disabled. This provides robustness in the model response (Hung, 1998a; Khosroyani, 2000). Reprinted from Hung *et al*. (1986) with the permission of © IEEE.

the response delay time, where the target will be after a sampling interval and generates a step signal to correspond to the new target position. For example, for a ramp stimulus, the predictor uses the target position and velocity information to estimate where the target position will be after a sampling interval, and generates a characteristic step response which matches the target at the end of the sampling interval. If the ramp target continues, the predictor must repeat its calculation during each sampling interval so that the resulting staircase-like step response will match the instantaneous ramp stimulus amplitude. For a very fast stimulus, which begins and then stops, as in step and fast ramp-step stimuli, the predictor predicts the final stopped value, and generates a step signal to the final position. For signals that regularly alternate, as in sinusoidal stimuli, the predictor serves another function. It reduces the time required for estimating the target position by reducing DELAY2, and hence decreases the phase lag between the accommodation stimulus and response, thus representing the effect of anticipation. The block diagram of the slow component is shown in Fig. 4(c). The slow component is driven by accommodation error, delayed by 370 ms, and has both a magnitude and velocity limiter to reflect the range of operation of the slow process. Its dynamics are modeled by a first-order lag element. The slow component acts over small amplitude and velocity ranges and uses negative feedback to provide the error signal for the controller. The fast and slow components operate under separate stimulus regimes so that when one is active the other is disabled. This provides robustness in the simulated accommodation response. The output of the fast, slow components are summed and fed into the plant of the system, which represents the dynamics of zonule, ciliary muscles, and lens. Experimental results from ciliary muscle stimulation in monkeys show that the plant can be represented by a first-order element with a time constant of 0.3 s (Hung *et al.*, 1982).

4.2. ***Simulation results.*** The dual-mode model simulations are in reasonably good agreement with previously reported experimental observations (Campbell and Westheimer, 1960; Kasai *et al.*, 1971; Hung and Ciuffreda, 1988). The pulse responses increase in amplitude and duration with increasing pulse duration. The rise time of the step response is about 200–250 ms and the steady-state error is quite small [Fig. 5(a)]. The ramp responses exhibit a transition from smooth tracking for slower (0.5 to 1.5 D/s) stimuli to staircase-like steps for faster (2 to 5 D/s) stimuli [Fig. 5(b)]. Sinusoidal responses show a transition from smooth tracking for lower frequency (0.05 to 0.1 Hz) stimuli to combined smooth tracking and steps for higher frequency (0.1 to 1.5 Hz) stimuli [Fig. 5(c)]. For periodic stimuli, such as sinusoids, after about two cycles the predictive mode comes into effect and there is a reduction in latency, indicating anticipation.

To illustrate the effects of the fast and slow components, their individual contributions to the response are shown for selected stimuli in Fig. 6 for: (a) 0.5 Hz square wave; (b) 2 D/s ramp; and (c) 0.3 Hz sine wave. Note that the slow component comes into play primarily at the end of the large fast component movements.

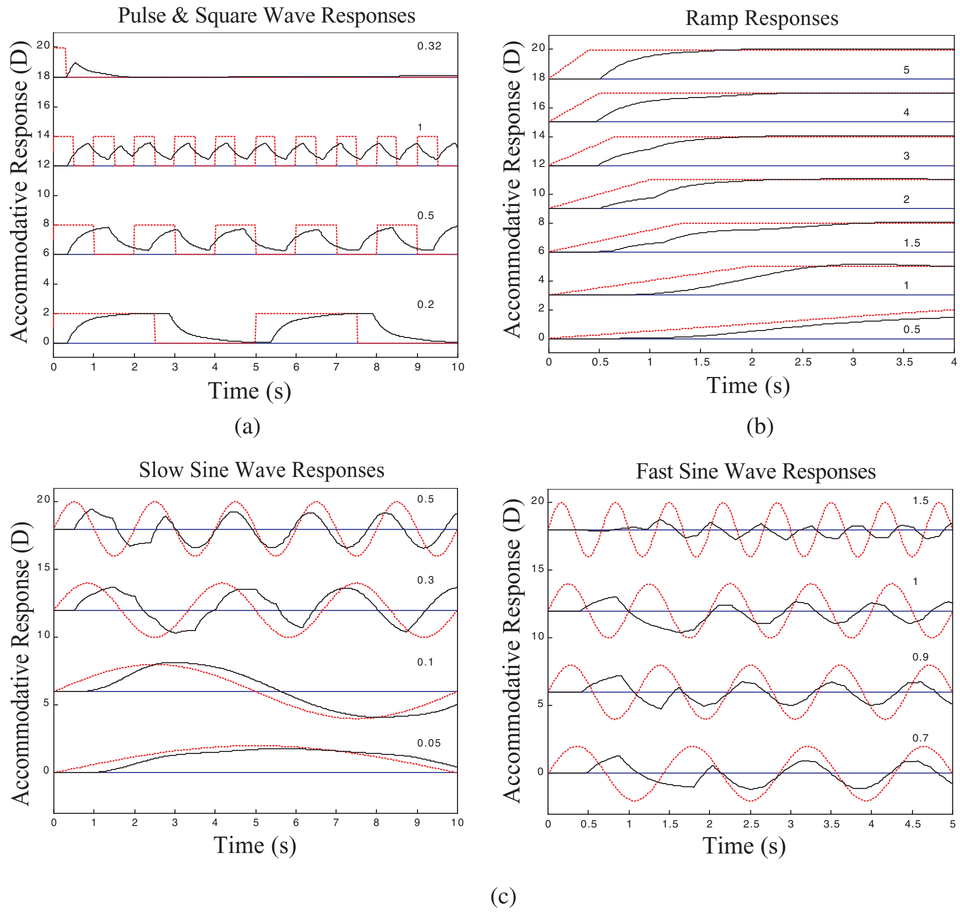

Figure 5. Dual-model accommodation model simulation responses to: (a) pulse (top trace, 0.32 s stimulus duration) and square-wave stimulation (frequency, in Hz, is shown at right of traces) of 2D amplitude; (b) ramp stimulation (velocity, in D/s, is shown at right of traces) with maximum amplitude of 2D; and (c) sine-wave stimulation (frequency, in Hz, is shown at right of traces) for +/−2D peak-to-peak amplitude (Khosroyani, 2000). Dashed lines represent the stimulus, and continuous lines represent the response. Horizontal lines represent zero level of accommodation.

In the case of the 0.3 Hz sinusoidal stimulus, the slow component contribution is zero. Also note that the total accommodative response represents the output of the fast and slow components through the plant dynamic element. Hence, even when only the fast component is present, so that abrupt changes occur in the controller signal, the total accommodative response still exhibits relatively slow dynamics.

5. Discussion

There is neurophysiological evidence for the dual-mode process. Poggio and Fischer (1977) found in the visual cortex of the alert monkey binocularly driven

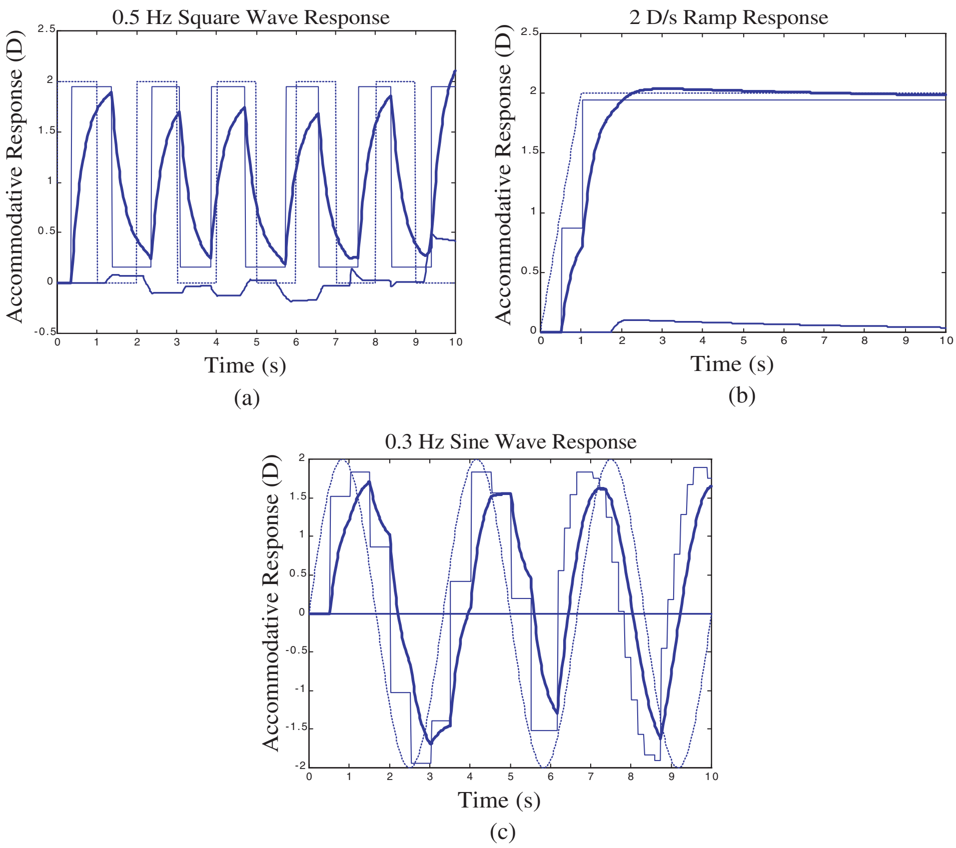

Figure 6. Illustration of fast and slow component dynamics for selected stimuli: (a) 0.5 Hz square wave; (b) 2 D/s ramp; and (c) 0.3 Hz sine wave. For these figures, the accommodative stimulus is shown as dashed (- -); the fast component is shown as thin solid (—); the slow component is shown as medium solid (**—**); and the total accommodative response, which represents the combined effects of the fast and slow components through the plant, is shown as thick solid (**▬**) lines.

'near' and 'far' cells that were most responsive when the target was more than 1 deg nearer or farther, respectively, from the initial fixation plane. In addition, 'tuned excitatory' cells were found that fired maximally when the visual stimulus was at the same distance as the fixation point; and 'tuned inhibitory' cells were found to discharge most vigorously when the stimulus was either just in front of or just beyond the fixation plane (i.e., less than ± 1 deg). Thus, the fast component corresponds to the near and far cells, which would initiate the movement by driving the response in the appropriate direction. The slow component corresponds to the tuned cells, which would send the appropriate excitatory and inhibitory signals to maintain fixation.

Dual-mode behavior has also been observed in other physiological systems. For example, the human manual control system also exhibits fast open-loop and slow closed-loop components (Stark, 1968). This can be seen in a grasping motion such as reaching for and picking up a pencil. The initial reaching motion is a rapid open-loop preprogrammed motion of the arm and hand to bring them near the pencil. Subsequently, the fingers are brought together under slower visual and proprioceptive feedback control to grasp the pencil. Such a dichotomy between fast and slow components in physiological systems appears to provide the required rapid responsivity for initially approaching a target without feedback oscillations due mainly to the relatively long latency, and the sensitivity and accuracy needed to acquire the target. Thus, it is perhaps not so surprising that the dual-mode model developed for the vergence system can be readily applied to the accommodation system using appropriate selection of parameter values.

This dual-mode dynamic model of accommodation is the first to simulate accurately experimental responses to a variety of stimuli. Previous models simulated only certain stimuli, such as steps or sinusoids, but not all the different types of stimuli and not with the accuracy exhibited in the present simulations. The present model was able to achieve this by separating the forward-loop into fast and slow components. Such a dual-mode process resulted in discontinuous behavior by dividing the responses into two distinct regimes of operation. The open-loop fast component responded rapidly to the stimulus based on its velocity and amplitude, and then the slow closed-loop slow component took over to attain as well as maintain an accurate response level. Moreover, such dual-mode behavior mimicked experimental accommodative response characteristics. This is especially seen in the ramp responses, which show accurate smooth tracking of the target for slow ramps, but staircase-like step responses to fast ramps [see Figs 5(b) and 6(b)]. The step amplitudes matched the anticipated ramp stimulus position based on the stimulus velocity. Further, for repetitive stimuli, such as square wave and sinusoids, the responses exhibited prediction by reducing the phase lag in the responses.

The robustness of the model can be seen in its ability to maintain stability and accuracy while achieving multiple goals. For example, it must exhibit discontinuous behavior (e.g., multiple-step responses to ramp stimuli), guide the response automatically (i.e., using only the model software) by predicting target position based on its velocity and to reduce phase lag for repetitive target pattern, and also attain an accurate steady-response level. The model achieves this by having two separate stimulus regimes for the fast and slow components. When one is active, the other is inactivated. Thus, there is no overlap of responses by the fast and slow components, which would have caused conflicting commands and potential response instability. It should be pointed out that the previously observed 2 Hz accommodative oscillations under steady viewing conditions (Campbell *et al.*, 1959; Charman and Heron, 1988) has been shown to be an artefact of the arterial pulse on the accommodation measurement device (Winn *et al.*, 1990).

This model can be used to simulate clinical dysfunction such as accommodative insufficiency. Variation in certain model parameter values that simulate accommodative insufficiency may provide insight into the underlying causes of the dysfunction. For example, a previous static accommodation was able to simulate static amblyopic behavior by reducing the gain in the forward loop (Hung *et al*., 1983). For the present model, dynamic parameters, such as controller or plant time constants, as well as other static parameters, such as the depth of focus and tonic accommodation (Morgan, 1968; Hung and Ciuffreda, 1994), could be varied to simulate symptomatic behavior. In this way, the model may be used to answer the question as to whether it is sensory, motor, or higher-level deficit that results in accommodative insufficiency. Indeed, this is an active area of research both in basic science and in the clinic.

The dual-mode dynamic model of accommodation can now be combined with the complementary model for vergence to provide a comprehensive interactive dual-feedback dynamic model of accommodation and vergence. Previously, a static interactive dual-feedback model (Hung and Semmlow, 1980) had provided important insights into basic understanding of oculomotor behavior such as fixation disparity, phoria, AC/A, and accommodative stimulus/response function (Hung, 1997, 1998b), as well as clinical conditions such as amblyopia, strabismus (Griffin, 1976; Ciuffreda, 1991; Benjamin, 1998). The combined dynamic model may provide new insights into dynamic oculomotor behavior, such as clinical flipper rates, prism vergence tests, and accommodative and convergence insufficiency.

6. Summary and Conclusions

This is the first model to simulate accurately the dynamic characteristics of the accommodation system to a variety of stimuli such as pulse, step, ramps, and sinusoids. The structure of the model was based on an earlier successful dynamic model of the vergence system (Hung *et al*., 1986; Hung, 1998a). Parameters were modified from the earlier model to fit the characteristics of the accommodation system. A MATLAB/SIMULINK program was used to simulate the accommodative dynamic responses. This dynamic model can serve as a standard for quantitative analysis of normal accommodative behavior and as the basis for simulating accommodative anomalies such as amblyopia and accommodative insufficiency to provide greater quantitative insight into the mechanisms underlying these accommodative deficits. Finally, this model can be combined with the vergence dynamic model to provide a comprehensive model of the oculomotor near response.

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