Active Control With an Isoluminant Display

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***Abstract*—Humans perceive isoluminant visual stimuli (i.e., stimuli that show little or no luminance variation across space) to move more slowly than their luminance-defined counterparts. To explore whether impaired motion perception at isoluminance also affects visuomotor control tasks, the authors examined the performance as humans actively controlled a moving line. They tested two types of displays matched for an overall salience: a luminant display composed of a luminance-defined Gaussian-blurred horizontal line and an isoluminant display composed of a color-defined line with the same spatial characteristics, but near-zero luminance information. Six subjects were asked to use a joystick to keep the line centered on a cathode ray tube display as its vertical position was perturbed pseudorandomly by a sum of ten sinusoids under two control regimes (velocity and acceleration control). The mean root mean square position error was larger for the isoluminant than for the luminant line (mean across subjects: 22% and 29% larger, for the two regimes, respectively). The describing functions (Bode plots) showed that, compared to the luminant line, the isoluminant line showed a lower open-loop gain (mean decrease: 3.4 and 2.9 dB, respectively) and an increase in phase lag, which can be accounted for by an increase in reaction time (mean increase: 103 and 155 ms, respectively). The performance data are generally well fit by McRuer *et al.'s* classical crossover model. In conclusion, both our model-independent and model-dependent analyses show that the selective loss of luminance information impairs human active control performance, which is consistent with the preferential loss of information from cortical visual motion processing pathways. Display engineers must therefore be mindful of the importance of luminance-contrast *per se* (not just total stimulus salience) in the design of effective visual displays for closed-loop active control tasks.**

***Index Terms*—Chromatic display, contrast, manual control, one-dimensional (1-D) motion, speed perception.**

I. Introduction

Since Ramachandran and Gregory [2] first reported loss of apparent motion of red–green isoluminant stimuli in random dot kinematograms, many other researchers have demonstrated that isoluminant color stimuli appear to move more slowly than luminant stimuli of the same physical speed [3]–[10]. Although it has clearly been established that human speed perception is compromised in passive speed estimation tasks for visual stimuli near isoluminance or at low contrast [11]–[13], human detection of small position offsets remains accurate and precise, even without luminance information [14]–[16]. It thus has been argued that to detect motion for isoluminant stimuli, observers may rely on position information. Indeed, when viewing low-contrast near-isoluminant color gratings, observers have reported that the motion appears jerky and difficult to differentiate from apparent motion, suggesting that the residual motion is perceived by monitoring the displacement of stimulus features over time [17], [18].

Despite the wealth of information from passive psychophysical testings, it remains unclear what impact degraded speed perception has on human performance in an active closed-loop control task under isoluminant conditions. Consider, for example, an actual vehicular control such as when a helicopter pilot, among other tasks, must stabilize the horizon displayed on a panel to hover at a constant position while facing random perturbations produced by wind. If the cockpit display system relies on color information (without sufficient luminance contrast) to depict the virtual horizon, how might this affect the pilot's control performance?

In passive speed-matching tasks, one can force observers to rely exclusively on motion information to perform the task by randomizing the temporal duration and the initial position of the moving visual stimulus to make the position information irrelevant (e.g., see [19]). In active control of a moving stimulus, however, it is difficult to separate an operator's reliance on target speed from that on target position. Visual feedback of target speed and position could both be used to continuously adjust the controller to perform the task. Thus, although an operator's perception of target speed is compromised at isoluminance, control performance might not be affected much because of the accurate perception of target position.

In this paper, we used a closed-loop manual control task to investigate the effect of isoluminance on active control. Specifically, we used a task in which subjects were asked to use a joystick to control a moving horizontal luminance- or color-defined line whose vertical position was perturbed in a pseudorandom manner. Although this task is quite simplified, it shares essential features with the aforementioned real aerospace horizon control task. We systematically examined the effect of isoluminance on control performance under two different control regimes. In the velocity-control regime, the joystick displacement generated a command affecting the rate of change of line position; in the acceleration-control regime, the joystick displacement generated a command affecting the rate of change of line velocity. Velocity control is commonly experienced in many modern-world situations, e.g., control of an automobile in which the rate of change of direction is proportional to the steering wheel displacement. Acceleration control, although less common, less intuitive, and therefore more challenging, can be mastered with practice, e.g., control of a spacecraft [20].

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Given that velocity control only requires the operator to respond to the line position, while acceleration control requires the operator to use feedback of the line velocity for accurate closed-loop performance [20], [21], one might expect the different joystick command dynamics of the two control regimes to influence the type of information subjects rely on for control performance. Thus, the compromised speed perception at isoluminance might preferentially affect acceleration control. However, in a previous study, we found that varying the luminance contrast of a monochromatic line affected the control performance similarly for velocity and acceleration control, as the low contrast likely affected both position and speed information [22]. In the present experiment, given that any degradation in speed perception at isoluminance was not accompanied by a general decrease in salience or degradation in the position information, we were able to perform a more direct examination of the role of speed information *per se* in the active control of a moving line. To quantitatively evaluate how isoluminance affects the subject's use of speed and the position information, we modeled their performance data using a crossover model [1], tailored to assess the specific visual cues used to support performance [21].

II. Methods

A. Participants

Six staff members (four naive as to the specific goals of the paper) at the NASA Ames Research Center participated in the experiment. All subjects had normal or corrected-to-normal visual acuity and normal color vision, i.e., they all had 20/20 foveal acuity and accurate performance on the color arrangement tests [23].

B. Stimulus Generation and Control

Two types of display stimuli were used: a "luminant line," a luminance-defined (gray) Gaussian-blurred ($\delta = 0.5^\circ$) horizontal line (34° H $\times$ 1.8° V); and an "isoluminant line," a color-defined (blue) line with the same spatial characteristics but near-zero luminance contrast. Both stimuli were displayed on a uniform gray background of 22 $\mathrm{cd/m^2}$ on a FlexScan F980 Eizo 19-in cathode ray tube (CRT) monitor (1240 $\times$ 1028 pixels, 34° H $\times$ 26° V) at 60 Hz. For the luminant line, the luminance contrast was 8%, defined by the Michelson contrast formula $(\mathrm{Lum_{max}} - \mathrm{Lum_{min}})/(\mathrm{Lum_{max}} + \mathrm{Lum_{min}})$, where $\mathrm{Lum_{max}}$ is the luminance of the line and $\mathrm{Lum_{min}}$ is the luminance of the background. For the isoluminant line, the chromatic contrast is expressed in terms of the modulation of the long-(L), middle-(M), and short-(S) wavelength sensitive cones. To illustrate, suppose the L cone excitations for the line and the background are $\mathrm{L_{max}}$ and $\mathrm{L_{min}}$, respectively. The L cone contrast is defined as $(\mathrm{L_{max}} - \mathrm{L_{min}})/(\mathrm{L_{max}} + \mathrm{L_{min}})$. When generating the isoluminant line, we kept the contrast for the L and M cones at 0 and the contrast for the S cones at approximately 20%. Prior to the experiment, we individually determined the isoluminant point for each subject using the minimum motion technique (which utilizes apparent motion for matching the luminance of different colors) [24].

TABLE I
MAGNITUDES AND FREQUENCIES OF THE TEN HARMONICALLY INDEPENDENT SINUSOIDS IN THE INPUT POSITION PERTURBATION u

i	a_i	k_i	ω_i (Hz)
1	2	5	0.021
2	2	8	0.033
3	2	13	0.054
4	2	23	0.096
5	2	37	0.154
6	2	59	0.246
7	0.2	101	0.421
8	0.2	179	0.746
9	0.2	311	1.296
10	0.2	521	2.171

Both the luminant and isoluminant lines were about 3–4 times detection threshold for such stimuli [25]–[27].

During a trial, the participant was asked to use a joystick (B&G Systems, JF3) to keep the line centered on the monitor screen as its position was perturbed by the sum of ten harmonically independent sinusoids. We removed the springs from the joystick to favor a more continuous control response. The input position perturbation u had the following form as a function of time t:

$$u(t) = \sum_{i=1}^{10} D \frac{a_i 2\pi k_i}{240} \sin\left(\frac{2\pi k_i}{240} t + \rho_i\right). \quad (1)$$

Table I lists the actual values of a, k, and resulting frequencies ($\omega = 2\pi k/240$) used for the paper. D was set to a value of 0.8°, and the phase offset (ρ_i) was randomly varied from $-\pi$ to π. The use of harmonically independent sum-of-sines not only made the line motion on the screen appear random, but also allowed for a frequency-based analysis of the linear component of the control response while minimizing artifacts from nonlinearities that might produce harmonic distortion. The average speed of the uncorrected input disturbance was $2.25^\circ/\mathrm{s}$ (peak: $8.51^\circ/\mathrm{s}$).

Two types of joystick control regimes were tested; the displacement was proportional either to the rate of change of line position (velocity control) or to the rate of change of line velocity (acceleration control). The control regimes of the joystick were specified by the controlled element dynamics $\mathrm{Y_c}$ (Fig. 1), implemented in software by the display computer with

$$\mathrm{Y_c} = \frac{1}{s} \quad (2)$$

for velocity control and

$$\mathrm{Y_c} = \frac{1}{s(s+0.2)} \quad (3)$$

for acceleration control. Note that our acceleration control is not a perfect acceleration control system of $1/s^2$. We added a damping factor of $0.2s$ to reduce task difficulty. The joystick position was sampled at 60 Hz, i.e., every frame of the display. Thus, the system feedback delay was 1 frame or

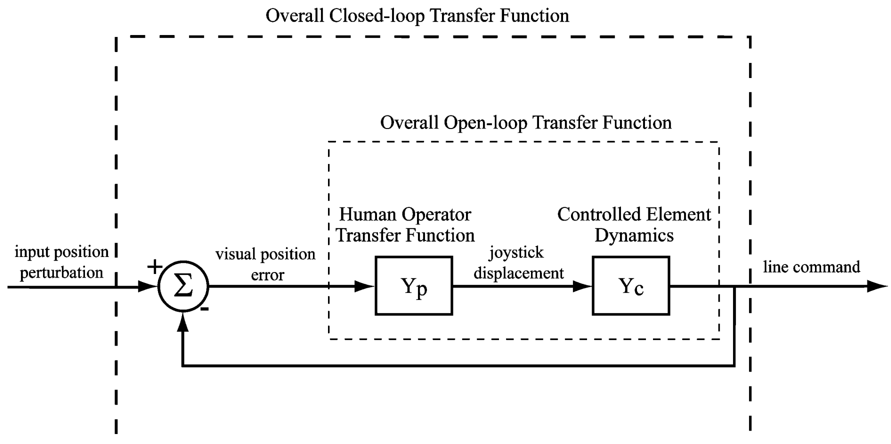

Fig. 1. Simplified block diagram of our active control task. The human operator transfer function captures the operator's control compensation, and the controlled element dynamics specifies the joystick control regimes.

16.67 ms, which is a small fraction of the total human reaction time. Joystick displacement values ranged from -1 to 1, corresponding to the full backward and forward positions, respectively.

C. Procedure

On each trial, a stationary line appeared and began moving when the subject pulled the joystick trigger. The line initially moved according to the sum-of-sines perturbation input but this line motion was reduced as the subject's task was to move the joystick forward and backward to keep the line centered on the monitor screen. The duration of each trial was 245 s.

Each subject ran two experimental sessions on two different days. Each session consisted of four conditions (2 display types $\times$ 2 control regimes) with three trials per condition and typically lasted about 1 h. Trials were blocked by control regime and display type, and the testing order of a control paradigm and display type was counterbalanced. There was a 30-s break between trials and a 4-min break between blocks. To ensure that subjects understood the task and became familiar with the control regimes, they performed practice sessions until performance appeared stable before the experiment commenced.

D. Data Analysis

To investigate different aspects of the impact of isoluminance on the active control performance, we used several metrics. Raw total performance error was measured as the root mean square (RMS) of the time series of recorded line position error from the center of the screen in degrees of visual angle. For this analysis, the line position error was clipped at the maximum visual angle subtended by the screen. We analyzed the data beginning 5 s after the start of the trial to ensure that we skipped the initial transient response. To examine the operator's control response specific to the input perturbation frequencies, we performed frequency (Bode) analyses to compute both the closed-loop and open-loop describing functions from our closed-loop performance data (Fig. 1). For the closed-loop Bode analysis, we Fourier-analyzed both the input position perturbation and the line command to obtain the relevant signal amplitudes and phases. For the open-loop Bode analysis, we Fourier-analyzed both the visual position error and the line command to obtain the relevant signal amplitudes and phases. In both cases, we took the ratios of the amplitudes and the difference between the phases to compute the gain and phase lag, respectively, at each perturbation frequency, averaged across two sessions (six trials), for each display type. We then used the phase from the luminant display condition as the reference and computed the relative response delay in milliseconds for the isoluminant display. To determine the effect of isoluminance on performance, we conducted a repeated-measures analysis of variance (ANOVA) on each of the above performance metrics.

E. Modeling

Our closed-loop active control task allows subjects to use the visual feedback of both line speed and position to continuously adjust the joystick to minimize the line motion and position offset on the screen. To evaluate the effect of isoluminance on their use of speed and the position information in this active control task, we modeled the open-loop performance data using a modified McRuer crossover model, a simple linear dynamic model that describes the control compensation that humans provide for a wide variety of closed-loop manual control tasks [1]. To illustrate the model, a simplified block diagram of the system is shown in Fig. 1.

In the model, the control compensation provided by the human operator is captured by transfer function $\mathrm{Y_p}$

$$\mathrm{Y_p} = \frac{e^{-s\tau}(sK_\mathrm{v} + K_\mathrm{p})}{s^2/\omega_n^2 + 2s\xi_n/\omega_n + 1} \tag{4}$$

with τ representing the sum of the perceptual and motor delays that specify the operator's reaction time, K_v representing the operator's sensitivity to stimulus speed, K_p representing the sensitivity to stimulus position offset, parameters ω_n and ζ_n

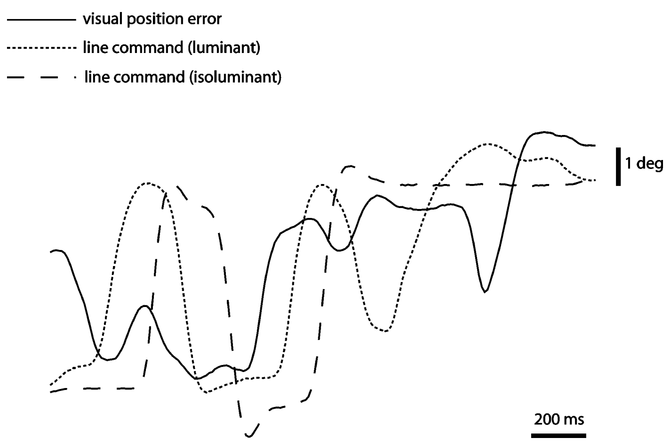

Fig. 2. Typical raw performance data of the input visual position error (solid line), the line command for the luminant (dotted line), and isoluminant (dashed) displays. Note that the output is a low-pass filtered and delayed version of the input.

representing the fixed second-order response dynamics of the operator independent of the visual stimulus, and s, the Laplace transform variable.

Model parameters were determined by a best fit to the open-loop describing function using a weighted (by standard error) least-squares procedure (see [21] for details). We fixed ω_n and ζ_n across all four conditions such that there were only 14 degrees of freedom to fit 80 data points for each subject. We excluded subject AEK from the modeling analysis because he exhibited different control strategies for the two control regimes, making comparison across control regimes problematic. For the rest of the five subjects, the Pearson correlation coefficients between the model estimates and the performance data ranged from 0.89 to 0.9966. This indicates that between 79% and 99% of the variance in the performance data can be accounted for by the crossover model. The reduced χ^2 for the model estimates, however, ranged from 4.83 to 9.22 across subjects, indicating that although the simple linear crossover model is a reasonably good fit to the data, it does not fully account for all aspects of performance. Indeed, it cannot account for any nonlinearities.

III. Results

A. Overall Performance

Fig. 2 plots typical raw data of the visual position error and the line command during a typical velocity control trial. In general, as expected, the joystick response is a scaled and delayed version of the input visual error signal, with a clear falloff in the response at the higher frequencies. Furthermore, the longer response delay for the isoluminant display is evident in raw data.

The mean RMS error averaged across six trials is plotted against display type for each subject in Fig. 3. A 2 (display type) × 2 (control regime) repeated-measures ANOVA on RMS error revealed that both the main effects of control regime and display type were significant, with $F(1,5) = 54.91$, MSE $=$ 0.24, $p < 0.001$ and $F(1,5) = 31.64$, MSE $= 0.07$, $p < 0.01$, respectively. As expected, the RMS error for velocity control was smaller than that for acceleration control (mean: 1.79° versus 3.28°), consistent with the latter's greater difficulty. The RMS error for the luminant display was significantly smaller than that for the isoluminant display (mean: 2.24° versus 2.83°), indicating that overall performance with the luminant line was better than that with the isoluminant line. The interaction between display type and control dynamics was also significant, with $F(1,5) = 8.35$, MSE $= 0.04$, $p < 0.05$. A separate t-test for dependent samples revealed that the increase in RMS error at isoluminance for acceleration control (mean ± SE across subjects: 29 ± 6% larger) was significantly larger than that for velocity control (mean ± SE across subjects: 22 ± 3%), $t(5) = -2.89$, $p < 0.05$, indicating the greater overall impact of isoluminance in the acceleration-control regime.

The RMS error measures the total performance error, both visually and nonvisually driven, and does not distinguish between errors due to an inappropriate response amplitude from those due to reaction time. The errors specific to the perturbation frequencies, however, are a better measure of the visually driven response specific to the moving visual stimulus, and Fourier analysis allows us to segregate response-amplitude and reaction-time effects. To depict how the control response varies with display type at each of the input temporal frequencies, we computed the closed-loop describing function (i.e., the ratio of the Fourier transform of the line command to that of the input position perturbation; see Fig. 1). Fig. 4(a) and (b) plot closed-loop gain and phase as a function of perturbation temporal frequency for naive subject RNE. The frequency-response (or Bode) plot shows that, for both velocity and acceleration control, gain is near unity (∼0 dB) with little phase lag (∼0°) at low frequencies and shows progressive roll-off at higher frequencies. In addition, gain is larger and phase lag is smaller for the luminant than for the isoluminant display, especially in the high-frequency range. These overall features are similar for all six subjects and the mean response is illustrated in the describing functions averaged across subjects in Fig. 4(c) and (d). The closed-loop performance can be characterized in terms of bandwidth (defined as the frequency at which gain falls below −3 dB). A 2 (display type) × 2 (control regime) repeated-measures ANOVA on bandwidth revealed that only the main effect of display type was significant ($F(1,5) = 28.85$, MSE $= 0.0005$, $p < 0.01$). Overall, the bandwidth for the isoluminant display was significantly smaller than that for the luminant display (mean reduction: 0.5 Hz), indicating that the performance starts to degrade at a lower stimulus temporal frequency with the isoluminant display.

B. Open-Loop Performance

The closed-loop performance of any negative feedback systems is designed to be robust to large differences in the internal workings of the system (i.e., negative feedback generates near unity closed-loop gain over a wide range of internal gains and therefore obscures how well the internal system is performing). To further analyze how well our subjects were performing at each of the perturbation frequencies, we also computed the

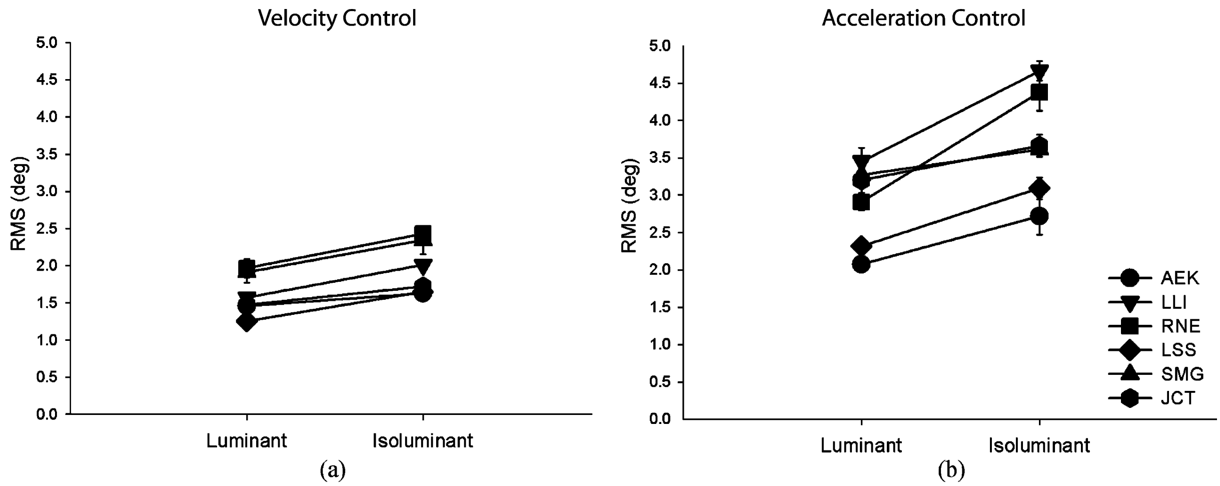

Fig. 3. Mean RMS error against display type for (a) velocity control and (b) acceleration control. Error bars represent SEs across six trials.

open-loop describing function (i.e., the ratio of the Fourier transform of the line command to that of the visual position error; see Fig. 1). Fig. 5(a) and (b) plot the overall open-loop gain and phase as a function of frequency for a naive subject RNE. Similar to the closed-loop data, the open-loop describing functions show overall low-pass characteristics with gain larger and phase lag smaller for the luminant than for the isoluminant display. Unlike the closed-loop gain, the open-loop gain tends to be > 1 (> 0 dB) and the command phase lags the input by about 90° at low frequencies, and both gain and phase roll off faster at high frequencies [20]. Again, these overall features are similar for all six subjects and are illustrated in the describing function averaged across subjects in Fig. 5(c) and (d).

To quantify the change of gain with display type, we plotted gain averaged across subjects against display type for each of the frequencies ≥ 0.1 Hz [Fig. 6(a) and (b)]. We ignored gains at the lowest three frequencies (0.02, 0.03, and 0.05 Hz) because our performance measurements were noisy at these ultralow frequencies. The large measurement uncertainty at these low frequencies was due to the fact that there were so few cycles available for Fourier analysis given the limited duration of a trial. A 2 (display type) $\times$ 2 (control regime) repeated-measures ANOVA on the gain averaged across frequencies revealed that only the main effect of display type was significant ($F(1,5) = 44.67$, $\text{MSE} = 1.31$, $p < 0.01$). Overall, the mean gain for the luminant line was about 1.5 times that for the isoluminant line (-1.59 versus -4.72 dB), indicating that performance with the luminant display was better than that with the isoluminant display. The mean decrease ($\pm$SE across subjects) in gain for the isoluminant line was 3.39 ± 0.39 dB for velocity control and 2.86 ± 0.68 dB for acceleration control. The decrease in gain for the isoluminant line at each frequency is plotted for each control regime in Fig. 6(c). A 7×2 repeated-measures ANOVA revealed that only the main effect of frequency was significant ($F(6,30) = 3.79$, $\text{MSE} = 23.85$, $p < 0.01$). *Post hoc* tests (Newman–Keul's) revealed a trend for both control regimes showing significantly larger ($p < 0.01$) gain decreases (i.e., bigger isoluminance effects) at the highest frequency.

To quantify the effect of display type on response phase, we first plotted mean phase averaged across subjects against display type for the three highest perturbation frequencies (0.75, 1.30, and 2.17 Hz) [Fig. 7(a) and (b)]. These frequencies were chosen because the display effect was most reliable there (see Fig. 5). Then, for each subject, we converted response phase to relative response delay by subtracting the phase lag of the isoluminant line from that of the luminant line then dividing the difference by the corresponding frequency. We plotted the relative delay with respect to the luminant line averaged across subjects as a function of the three frequencies in Fig. 7(c). Although the phases at the three frequencies are quite different [as can be seen in Fig. 7(a) and (b)], they nonetheless all correspond to similar relative response delays. A 3 (frequency) $\times$ 2 (control regime) repeated-measures ANOVA on relative response delays found that only the main effect of control regime was significant ($F(1,5) = 6.93$, $\text{MSE} = 3394.9$, $p < 0.05$). The overall relative response delay in the acceleration control condition is significantly longer than that in the velocity control condition (mean: 155 versus 103 ms).

C. Modeling

The crossover model allows us to perform a quantitative evaluation of the effect of isoluminance on the subject's use of visual speed and position information in our active control task. The velocity sensitivity $K_{\rm v}$ and the position sensitivity $K_{\rm p}$ capture the stimulus-dependent control characteristics subjects have in performing the task, and the time delay τ captures their reaction time to the moving visual stimulus (see [22, Fig. 8] for how varying $K_{\rm v}$, $K_{\rm p}$, and τ affects overall open-loop gain and phase for the two control regimes).

From the open-loop describing function, we estimated $K_{\rm v}$, $K_{\rm p}$, and τ for the human transfer function $\text{Y}_{\rm p}$ [Fig. 1 and (4)] for both display conditions and control regimes for each subject. Fig. 8 plots $K_{\rm v}$ and $K_{\rm p}$ against display type for each subject. A 2 (display type) $\times$ 2 (control regime) repeated-measures ANOVA on $K_{\rm v}$ revealed that only the main effect of display type was significant ($F(1,4) = 43.84$, $\text{MSE} = 0.000004$,

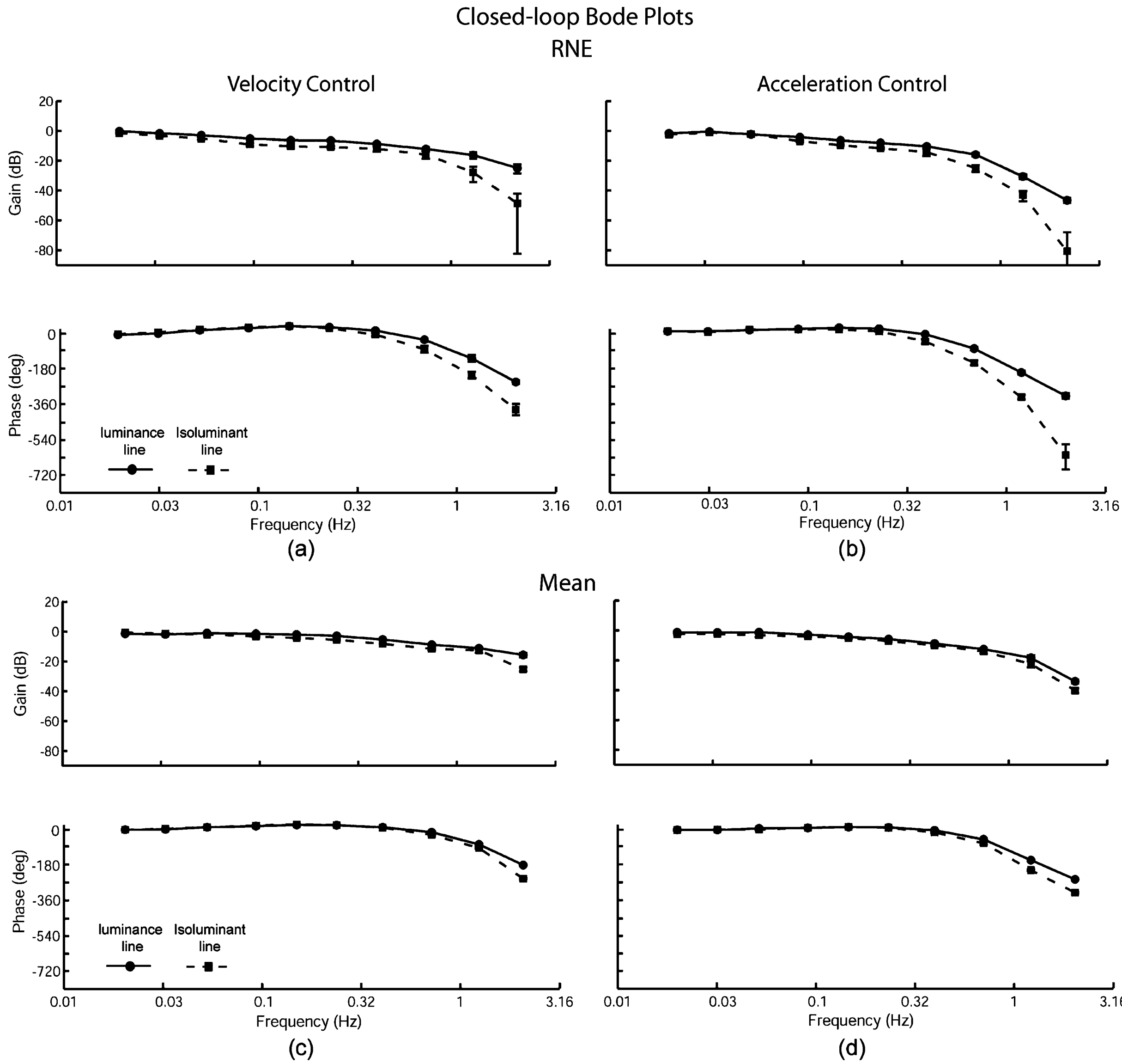

Fig. 4. Closed-loop describing functions. The upper panels depict mean gain and phase averaged over six trials as a function of perturbation frequency for a naive subject (RNE) for (a) velocity control and (b) acceleration control. Error bars represent SEs across six trials. The lower panels depict mean gain and phase averaged over six subjects as a function of perturbation frequency for (c) velocity control and (d) acceleration control. Error bars represent SEs across six subjects (some are smaller than the data symbols).

$p < 0.01$). As expected, K_v for the isoluminant display was significantly smaller than that for the luminant display (mean: 0.017 versus 0.024 % $\max/\deg \times \sec$),[1] indicating that subjects used speed information more effectively for the luminant display than for the isoluminant display. In contrast, a 2 (display type) $\times$ 2 (control regime) repeated-measures ANOVA on K_p revealed that only the main effect of control regime was significant ($F(1,4) = 13.91$, $\mathrm{MSE} = 0.00005$, $p < 0.05$). K_p for velocity control was more than twice as large as that for acceleration control (mean: 0.022 versus 0.010 % max/deg), confirming that subjects rely more on the position information to perform the task in the velocity control regime.

The model estimates of time delay τ are plotted against display type for each subject in Fig. 9. A 2 (display type) $\times$ 2 (control regime) repeated-measures ANOVA on τ revealed that only the main effect of display type was significant, with $F(1,4) = 20.55$, $\mathrm{MSE} = 0.004$, $p < 0.05$. Overall, τ for the luminant display was smaller than that for the isoluminant display (mean: 286 versus 415 ms). The mean increase in τ from the luminant to the isoluminant display for velocity control (106 ms) appeared to be smaller than that for acceleration control (152 ms), although unlike the model-independent analysis above, this effect did not reach significance.

IV. Discussion

Our model-independent and our model-dependent analyses both show that active control of a moving line is better for a

[1]We correlated visual position error and joystick displacement (before it goes through the control element $\mathrm{Y_c}$) to estimate the model parameters for the operator transfer function $\mathrm{Y_p}$. The units for position sensitivity K_p are thus % of maximum joystick displacement per degree of visual angle of the line position error on the screen. For velocity sensitivity K_v, these units are then multiplied by time in seconds.

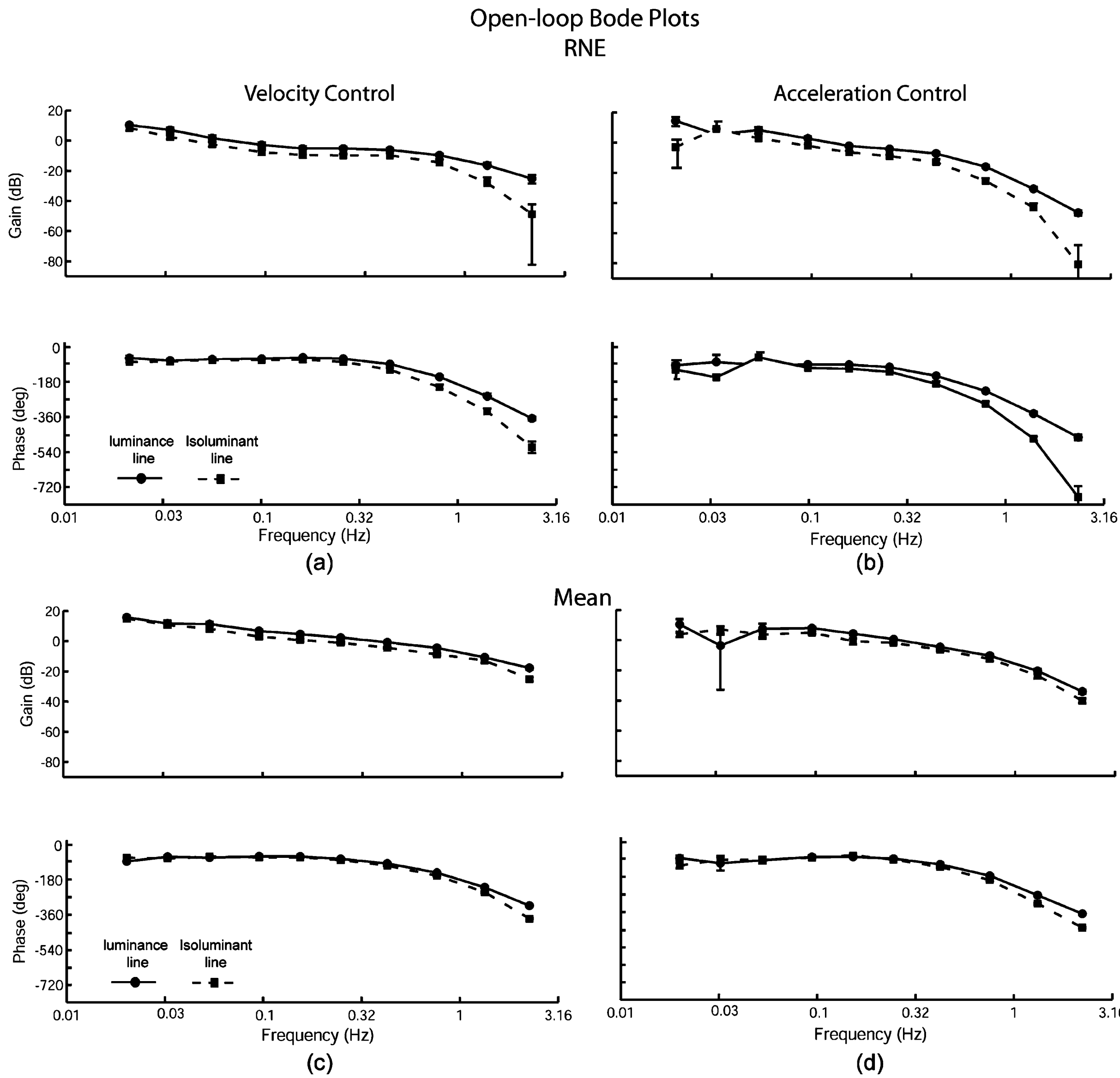

Fig. 5. Open-loop describing functions. The upper panels depict mean gain and phase averaged over six trials as a function of perturbation frequency for a naive subject (RNE) for (a) velocity control and (b) acceleration control. Error bars represent SEs across six trials. The lower panel depicts mean gain and phase averaged over six subjects as a function of perturbation frequency for (c) velocity control and (d) acceleration control. Error bars represent SEs across six subjects (some are smaller than the data symbols).

luminant display than for an isoluminant display. For an average perturbation speed of $2.25^{\circ}/\mathrm{s}$ using a linewidth of 1.8°, the isoluminant display produces a 22% and 29% rise in total RMS error, a 32% and 27% (3.4 and 2.9 dB) decrease in internal gain, and a 103 and 155 ms increase in reaction time, for velocity and acceleration control regimes, respectively. Our findings reinforce the fact that visual displays used for the closed-loop control of a moving target must be designed to meet the needs and constraints of the human visual system. In particular, for humans, not all visual salience is the same. Independent of any salience provided by color cues, a reasonable amount of luminance contrast is needed to support good tracking performance.

A. Reliance on Speed Information

We have recently found that humans use both speed and position information in the active control of a moving line [22]. The degraded control performance for the isoluminant line observed here is predominantly due to degraded speed information at isoluminance. First, the human ability to detect small visual position offsets does not change at isoluminance. Krauskopf and his colleagues [14], [15] measured vernier offset thresholds for Gabor patches and found that thresholds for stimuli defined by luminance variation and isoluminant chromatic variation were equal when spatial frequency and contrast relative to detection threshold were held constant, indicating that chromatic and luminance information are equally effective for position offset judgments. Furthermore, in our paper, the luminant and the isoluminant lines are of similar spatial characteristics and are both similarly suprathreshold. Thus, it is likely that they provide a comparable amount of position information for the active control task. Second, comparing the effect of isoluminance on previous passive speed-matching tasks with that in our active control task, we find that the magnitudes are similar.

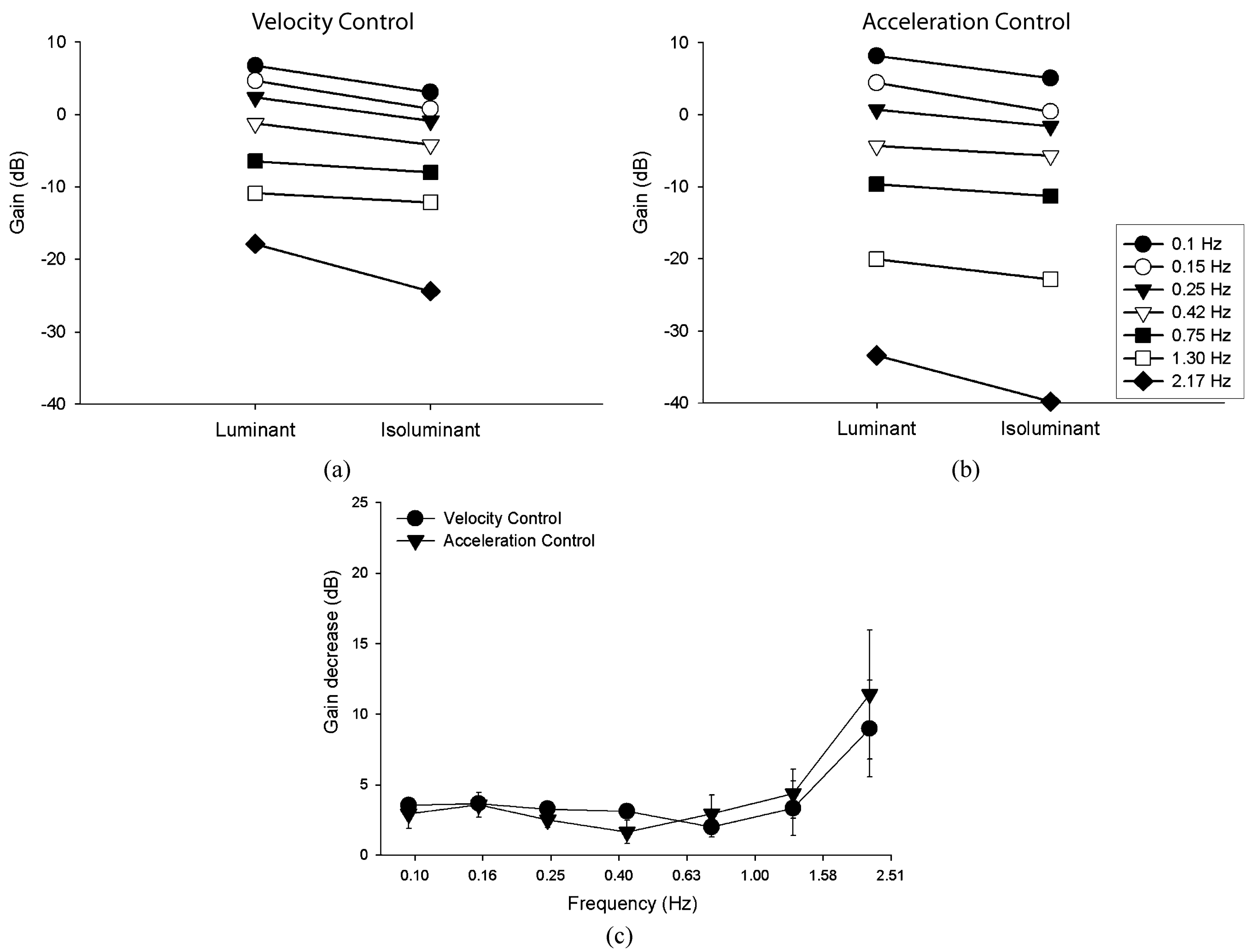

Fig. 6. Mean open-loop gain for the two types of displays averaged over six subjects for seven perturbation frequencies for (a) velocity control and (b) acceleration control. (c) Mean gain decrease from the luminant to the isoluminant display condition for the two control regimes as a function of perturbation frequency. Error bars represent SEs across six subjects.

Cavanagh *et al.* [5] found that when adjusting the speed of a 10% contrast luminant grating to match the speed of a red–green isoluminant grating, the red–green grating was perceived to move at about 40% of the speed of its luminant counterpart. Measuring reaction time to moving squares, Troscianko and Fahle [10] reported that the reaction times to moving stimuli were slower at isoluminance to an extent that implies that perceived speed at isoluminance was approxsimately 30% less than that seen at 8% luminance contrast. In our paper, the luminant line is at 8% luminance contrast, and the above numbers are in rough agreement with the amount of gain decrease ($\sim$30%) that we observed for the active control performance at isoluminance. Third, the open-loop analysis shows that the decrease in gain at isoluminance is larger at the highest stimulus perturbation frequency for both control regimes [Fig. 5(c)]. For equal amplitude perturbations, higher perturbation frequencies are associated with faster line oscillation speeds so this finding is consistent with the preferential loss of speed information at isoluminance. Fourth, while the existence of an isoluminance effect under both control regimes is consistent with our previous finding that speed information is used in both regimes [22], the larger effect on response delay and RMS error under acceleration control is consistent with the view that operators rely more on speed information for acceleration control [20], [21]. Finally, our model-based analysis is able to capture and segregate the characteristics of the speed and position sensitivity. The velocity (K_{v}) and the position sensitivity (K_{p}) reflect the subject's reliance on speed and position information, respectively. The fact that K_{v} is significantly smaller for the isoluminant display provides the most direct evidence that performance is less influenced by speed information at isoluminance.

B. Reaction Time

The model estimates of the time delay (τ) for the luminant display cluster in the range of 230–360 ms across the control regimes, which is within the expected range from previous manual control studies [21], [23], [28]. The isoluminance effect on the time delay of the model fit corresponds well to that obtained from our direct model-independent analysis of the describing functions (106 versus 103 ms for velocity control and 152 versus 155 ms for acceleration control). Likewise,

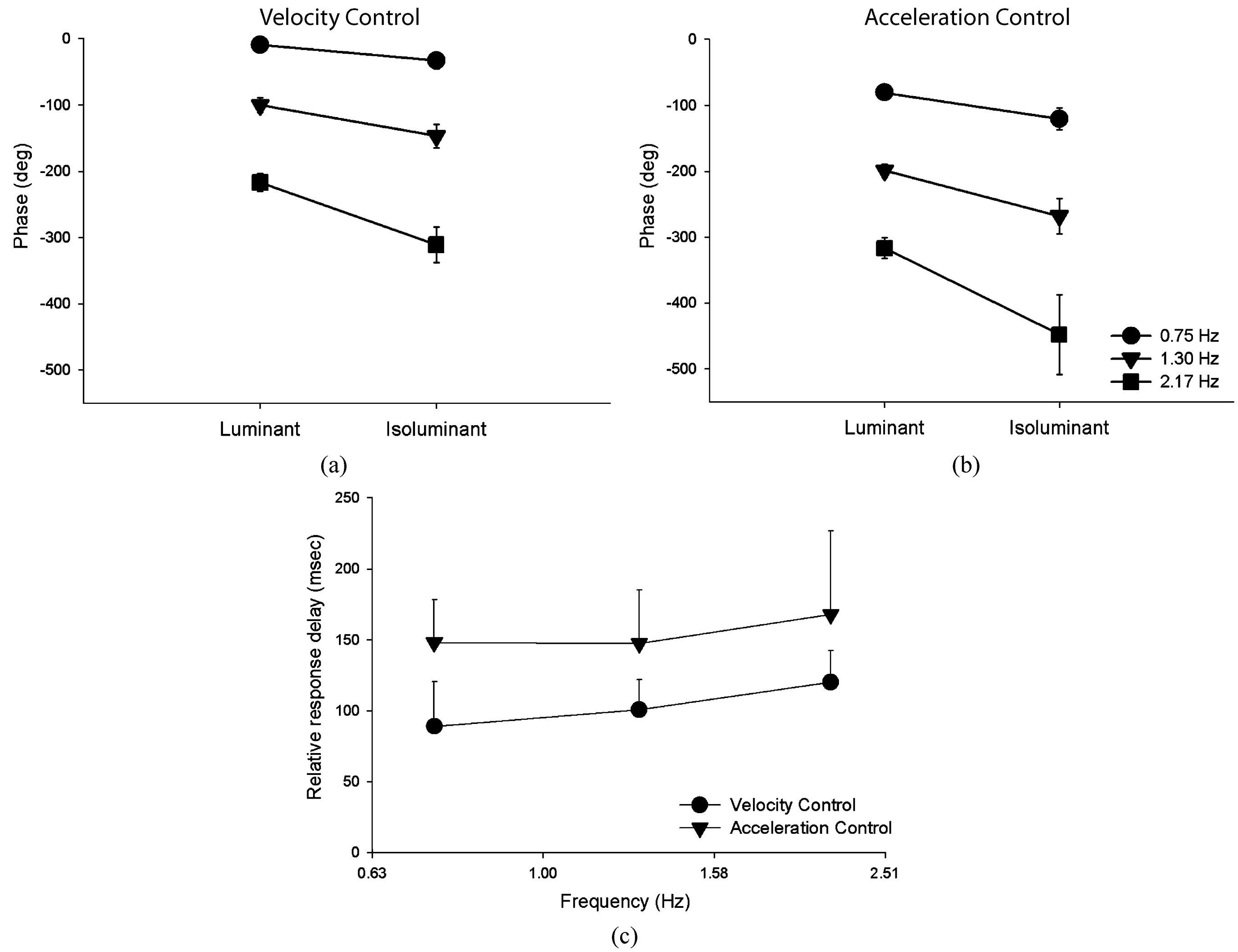

Fig. 7. Mean phase (degrees) averaged over six subjects for the three highest frequencies (0.75, 1.30, and 2.17 Hz) against display type for (a) velocity control and (b) acceleration control. Error bars represent SEs across subjects. (c) Mean relative response delay (milliseconds) for the two control regimes as a function of frequency. Only positive error bars are plotted.

previous studies have reported that isoluminance affects reaction times for motion detection. Specifically, Troscianko and Fahle [10] reported that for the velocity at about 2 deg/s, the reaction time for detecting motion offset for isoluminant stimuli was about 120 ms longer than that for a 8% luminance-contrast square (see [10, Fig. 5]), consistent with what we found in the current experiment. An isoluminance effect on reaction time has also been reported in studies on visuomotor control of eye movements. Mulligan [29] found that pursuit eye movement responses to luminance-defined suprathreshold targets had latencies on the order of 100 ms, consistent with many previous findings (e.g., [30]). However, the response latency increased on the order of 100–200 ms for color-defined isoluminant targets, similar to what we observed in the current experiment.

V. Conclusion

This paper provides a quantitative description, analysis, and model of the effects of isoluminance on a closed-loop manual control task. We conclude that: 1) human performance in active control of a moving line is seriously degraded at isoluminance, showing approximately a 25% increase in RMS error and a 30% decrease in internal gain; 2) the isoluminance effect is larger at high stimulus oscillation frequencies, consistent with the preferential loss of speed information critical for the active control of a moving line; 3) response sensitivity to stimulus speed decreases at isoluminance, indicating that speed cues are overall preferentially degraded at isoluminance; 4) lack of luminance-contrast information in the visual stimuli has a dramatic effect on reaction time, adding approximately 130 ms of delay; and 5) observed isoluminance effects are generally larger for acceleration than for the velocity control, consistent with the view that humans rely more on speed information for acceleration than for velocity control. Using the data reported here and in our recent parametric study of the effect of varying luminance contrast on manual control performance [22], display engineers can estimate the overall performance error, gain, and reaction time when visual luminance-contrast

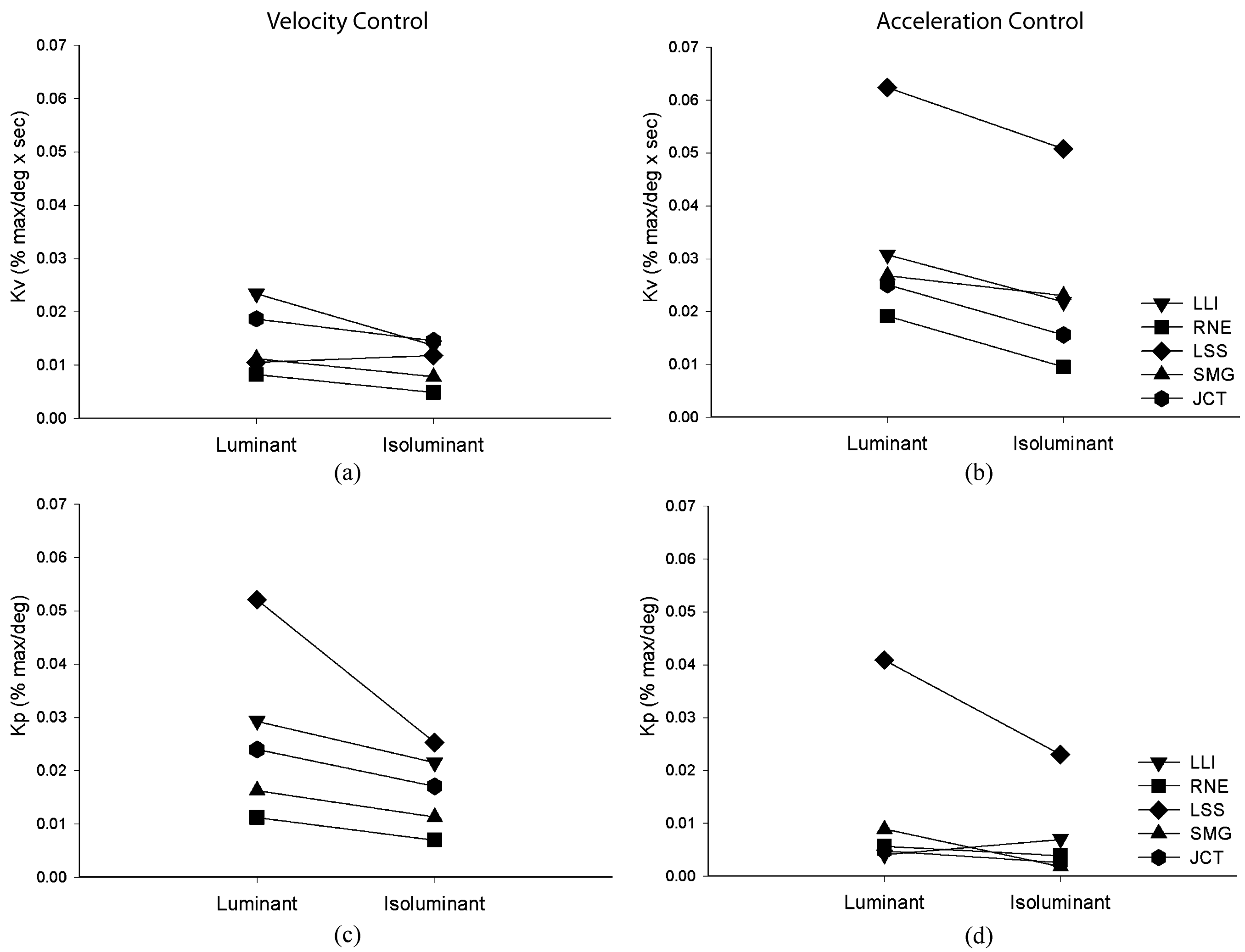

Fig. 8. Best-fitting model gain parameters against display type for each subject. K_{v} for (a) velocity control and (b) acceleration control. K_{p} for (c) velocity control and (d) acceleration control.

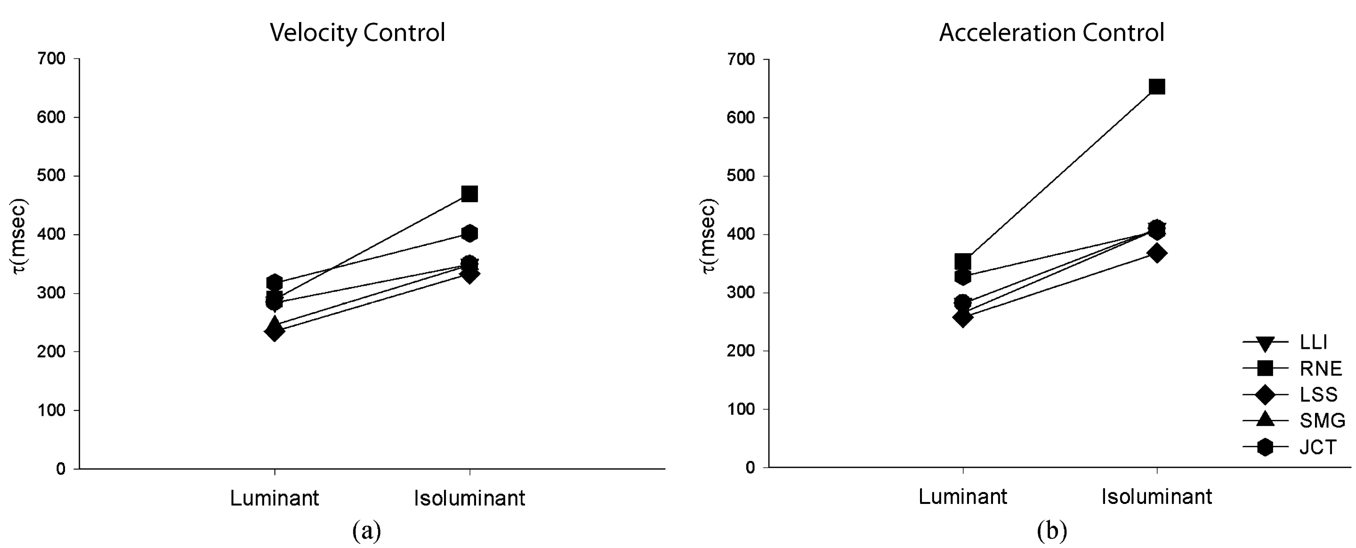

Fig. 9. Best-fitting model delay parameter τ for (a) velocity control and (b) acceleration control against display type for each subject.

cues are impoverished even when a overall salience is kept reasonably constant, with this paper specifically examining the worst case scenario. Interface and display designers must therefore take care to use adequate luminance contrast for their display elements, if they wish to support reasonably accurate and brisk tracking performance.

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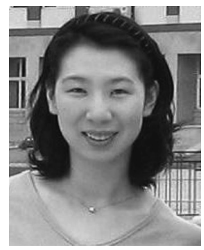

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