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Encoding Apparent Motion in Animated Mimic Displays

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Animated mimic displays represent system components, the physical connections between components, and the analogical flow of information or resources. These displays have the potential to improve the effectiveness of both training and real-time performance. One animation technique that is particularly efficient (from a computational perspective) is color table animation, which produces a subjective impression of movement through apparent motion. Display variables likely to influence the effectiveness of apparent motion were investigated in two experiments. The primary experimental manipulations were the levels of chromatic and luminance contrast in the displays (temporal frequency and direction of apparent motion were also varied). The results suggest that both types of contrast can be used to encode apparent motion but that luminance contrast is more effective. Several additional variables likely to influence the effectiveness of animation were held constant and are discussed briefly.

INTRODUCTION

Advances in computational technology are providing powerful new tools that expand the potential to provide decision support in complex domains. One use of this computational power is the development of expert systems that replace or complement human operators. An alternative is to develop decision support in the form of graphic displays. Graphic displays can facilitate performance by collecting and integrating relevant data, by providing alternative conceptual perspectives, by making the abstract concrete (the *envisionment* of information), and by restructuring an individual's view of the problem. The term *representation aiding* (Woods, 1991; Woods and Roth, 1988; Zachary, 1986) has been used to refer to this form of decision support.

To a large degree, technological problems associated with the implementation of representation aids have been resolved. Still to be developed are design approaches that allow the potential of representation aiding to be realized. A number of researchers have focused their efforts toward this goal (Bennett, 1992; Bennett, Toms, and Woods, 1993; Flach and Vicente, 1989; Rasmussen, 1986; Vicente and Rasmussen, 1990; Woods, 1991; Woods and Roth, 1988). They emphasize that effective displays will be designed only if both specific human capabilities and specific characteristics of the domain are considered. In particular, the goal is to map the domain semantics (the critical variables, the relationships between these variables, and the

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relevant goals and constraints) into a set of displays that allows the easy extraction or decoding of this information by the observer.

The cornerstone of this approach is the realization that in order to accomplish tasks in complex domains, an individual must consider the system from a number of different conceptual perspectives. Rasmussen (1986) developed a framework—the *abstraction hierarchy*—that can be used as a guide to developing representation aids (see also Flach and Vicente, 1989). The abstraction hierarchy has five levels of abstraction, or different conceptual perspectives, ranging from the physical form of a system (e.g., What are the system components? What do they look like? Where are they located?) to the higher-level purposes it serves (e.g., What is the system's purpose? Under what constraints does the system operate to fulfill this purpose?).

Configural displays are particularly effective at representing information at higher levels in the abstraction hierarchy (Bennett and Flach, 1992; Bennett, Toms, and Woods, 1993; Sanderson, Flach, Buttigieg, and Casey, 1989). Information at these levels is independent of the actual physical implementation. However, individuals will also require explicit information about the physical implementation. For example, imagine a process control application in which the level of a storage tank is low. To restore a normal level, the operator must consider the physical makeup of the system. What alternative resources are connected to the tank? How might these alternative resources be redirected to increase the level of the tank? What other system goals are compromised by doing so? This type of information corresponds to the level of physical function in Rasmussen's abstraction hierarchy, which he describes as "the physical (i.e., the mechanical, electrical, or chemical) processes of the system or its parts" (Rasmussen, 1986, p. 16).

One type of display that presents information at the level of physical function is the *mimic* or *pictorial* display. Mimic displays provide representations of the important components, systems, or subsystems and the physical connections among them. One example of this type of display is found in process control domains where static labels and markers are added to noncomputerized control panels to help operators understand the complex physical connections that exist in the system. Similar displays have been used to depict fuel, hydraulic, and electrical systems in aviation (Hawkins, Reising, and Gilmore, 1983; Stokes, Wickens, and Kite, 1990). Several exploratory systems have used computer-generated graphics to represent the flow of information or resources analogically. One of the most familiar examples is Steamer, an instructional system developed to teach propulsion engineering (Hollan, Hutchins, and Weitzman, 1984, 1987).

Figure 1a represents an animated mimic display that was developed for a difficult process control task (Bennett, 1992). This display was patterned after the animated mimic displays in Steamer.

It is important to distinguish between the screen updates that occur in traditional graphic displays and the animation of a mimic display. The term *animation* does not refer to the updating of digital values or analog indicators (e.g., changing the level of coolant inside the steam generator). In the present context it refers to the analogical representation of flow between system components.

In Figure 1 the perceptual characteristics of the graphical elements (the squares) inside the physical connections are shifted at discrete intervals. This produces a compelling impression of apparent motion that is found in some electrical signs, marquees, and airport runways. Apparent motion is "the experience of motion that occurs when at least two spatially separated stimuli are

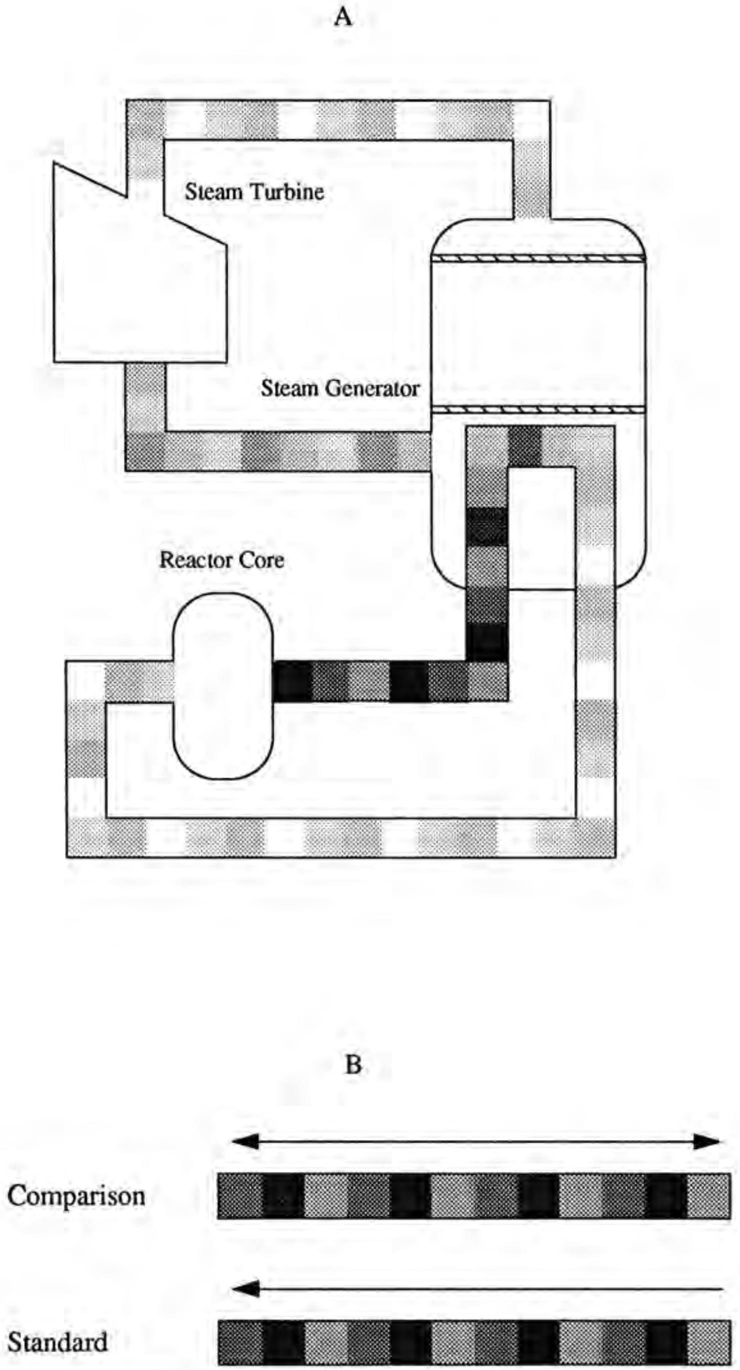

Figure 1. *An animated mimic display (A) and the standard and comparison bars (B) used in Experiments 1 and 2.*

alternately presented to an observer over time" (Petersik, 1989, p. 107).

Animated mimic displays have the potential to improve the effectiveness of real-time performance and the efficiency of training. These displays can improve real-time performance by (1) contributing to an individual's ability to assess current system state and the causal factors that underlie that state, (2) illustrating alternative system resources that can be used to avoid or recover from the violation of system goals, and (3) providing immediate feedback regarding the effectiveness of control input.

Animated mimic displays may play an especially critical role in computerized training systems for complex, dynamic domains. Hollan, Hutchins, and Weitzman (1984, 1987) emphasized that animated mimic displays can facilitate the development of appropriate mental models of complex system dynamics by providing a "simultaneous graphical explanation." Anderson (1988) also discussed the importance of this type of information for instructional systems designed to aid the development of causal reasoning skills.

At least part of the reluctance of designers to include animation in displays is attributable to the associated computational demands. In general, interactive animation (where the animation sequence changes in real time) requires powerful computing systems as well as specialized hardware and software. However, one technique that can be used to provide animation for mimic displays with less powerful computer systems and widely available hardware and software is color table animation (Mulligan and Stone, 1989; Shoup, 1979). Although there are more sophisticated uses of color table animation, a simple variation is color cycling (Shoup, 1979). In color cycling a static display is drawn that contains a number of spatially displaced graphical elements, each of which is associated with an index to color table random-access memory (i.e., the RGB values). Animation is produced by cycling these indexes systematically. Although the requirement for noninteractive animation sequences limits widespread application, this technique may be an efficient method to provide animation for systems in which the components and structural relationships remain fixed (e.g., process control, aviation).

Despite the potential benefits to real-time and training performance, very little empirical research has addressed fundamental issues in the implementation of animated mimic displays. From the perspective of display design outlined previously, the effectiveness of an animated mimic display will be determined by how well an individual is able to decode or extract the rate-of-flow information that has been encoded (or mapped) into the representation. Display variables that may be critical for effective animation include (but are not limited to) spatial frequency, temporal frequency, orientation, shape, wave form, luminance contrast, and chromatic contrast. The present study focuses on the role of luminance and chromatic contrast; a brief review of the relevant literature follows.

Apparent Motion

A great deal of evidence exists suggesting that there are two distinct processes in the perception of apparent motion: short-range and long-range processes (e.g., Petersik, 1989). One example of a long-range process is the phi phenomenon observed by early gestalt psychologists. The phi phenomenon refers to the fact that when two separate and stationary lights are turned on and off in succession, they will be perceived as a single light moving back and forth in space. Long-range processes operate on objects with large spatial separations, on objects that are presented both monoptically and dichoptically (Braddick, 1980), and even on objects that do not have the same shape (Kolers, 1963). Long-range processes are believed to result from central-processing mechanisms.

Short-range processes operate over much smaller spatial separations and do not operate with dichoptic presentation or with objects that change in shape. Braddick (1974) provided an example of short-range processes. He found that a clearly defined figure emerged when random dots were displaced uniformly over a small distance (approximately 15 arcmin) while the surrounding dots were displaced randomly. Short-range processes are believed to be the result of peripheral processing mechanisms and are responsible for the perception of real motion.

The usefulness of chromatic contrast for apparent motion depends on which of the two processes is operating. Early in the study of apparent motion, it was believed that long-range processes could use chromatic input, whereas short-range processes could not (Anstis, 1970; Braddick, 1980). For example, Ramachandran and Gregory (1978) replicated Braddick's experiment except that they used random dots that varied in chromatic contrast instead of luminance contrast. Under these conditions the figure did not emerge from the random dots. However, recent studies seem to indicate that chromatic input can be used by short-range processes (Gorea and Papathomas, 1989; Simpson, 1990). Lindsey and Teller (1990) summarized the ambivalent role of chromatic input for the perception of apparent motion by stating that "the impairment of motion perception at isoluminance is not all-or-none, but varies considerably with the specific motion perception task and with variation of stimulus parameters" (p. 1752).

In contrast, it is clear that luminance contrast is critical for the perception of apparent motion. Luminance contrast plays a central role in theories of motion processing and associated computational models. Nakayama (1985) stated, "An explicit biological model . . . would predict that the motion of any nonuniform luminance distribution could be seen" (p. 633). Although Nakayama qualified this statement subsequently, other empirical evidence points to the critical role that luminance plays in the perception of motion. For example, Kelly (1979) found that adding motion to sine wave gratings actually increased sensitivity to luminance contrast by a factor of two.

A fair amount of basic research has been performed to investigate chromatic and luminance contrast in motion perception. However, there are critical differences in the type of stimuli used to produce color table animation that may prohibit generalization. In general, sinusoidal wave forms—which produce relatively indistinct visual edges—have been used in the basic literature. Conversely, the designers of animated mimic displays (e.g., Hollan et al., 1984, 1987) have used wave forms with a *stairstep* luminance profile. These wave forms produce sharp visual edges that may influence contrast sensitivity. For example, Kelly (1975) investigated fusion thresholds for both a standard flicker fusion stimulus and a *bipartite* stimulus. The presence of a visual edge in the bipartite field altered the sensitivity curves dramatically for both luminance and chromatic contrast. In addition, many of these studies were conducted under much more controlled conditions (e.g., Kelly, 1979, obtained contrast sensitivity functions for moving sine wave gratings while stabilizing the image on the retina).

Two experiments were conducted to examine the effectiveness of chromatic and luminance contrast in providing apparent motion. Observers adjusted the rate of a comparison bar to match that of a standard bar; the luminance and chromatic contrast between the graphical elements was varied across trials. The direction of motion and temporal frequency were also varied.

EXPERIMENT 1

Method

Subjects. Four observers (one male and three female) participated in the experiment and were paid $5.00 an hour. Their ages ranged from 15 to 33 years, and all had normal or normal-corrected vision with no color blindness deficiencies. All observers had participated in three previous experiments using similar procedures but different stimuli (12 experimental sessions lasting approximately 40 min).

Apparatus. All experimental events were controlled by a general-purpose laboratory computer (Sun Microsystem 4-110). A 40.64-cm color video monitor (Sony Trinitron, model GDM-1604-15) with a resolution of 1152 × 900 pixels was used to present the stimuli and experimental prompts. The monitor had a refresh rate of 66 Hz, noninterlacing.

Stimuli. Two horizontal bars (see Figure 1b) were presented on a medium-gray background ($u' = 0.2126$, $v' = 0.4652$, $\text{cd/m}^2 = 3.64$). Each bar was 7.6 cm wide and 0.38 cm high; the bars were separated vertically by a distance of 4.8 cm and centered in the screen. The requirement to use an optical mouse ensured observer viewing distances between approximately 36 and 71 cm. The most comfortable seating position corresponded to a viewing distance of about 50 cm, which will be assumed in all calculations.

Each bar subtended a visual angle of 8.64 degrees horizontally and 26.13 arcmin vertically; the distance between the bars subtended a visual angle of 5.48 degrees. Each bar contained 20 graphic elements that were 0.38 cm high and 0.38 cm wide (subtending a visual angle of 26.13 arcmin both horizontally and vertically). Each bar contained three levels of chromaticity/luminance (CL) contrasts that repeated every third square (see Figure 1B). A cycle subtended a visual angle of 1.31 deg, producing a fundamental frequency of 0.77 c/deg.

The lower bar was the standard bar. The CL contrasts in this bar were shifted from the right to the left at a raw update rate of either 15 or 30 Hz throughout an experimental trial. Thus the temporal frequency of the standard bar was either 5 or 10 Hz, and the resulting velocity was either 6.53 or 13.06 deg/sec. The arrow in Figure 1B above the standard bar indicates that the graphical elements can be shifted only from right to left (the arrow was not present during the experiment).

The upper bar was the comparison bar, and its temporal frequency was controlled by the observer. At the beginning of a trial, the temporal frequency of the comparison bar was either 1.67 or 13.3 Hz, and the graphical elements could be shifted either to the right or to the left. The direction of apparent motion in the comparison bar remained the same during an experimental trial and could not be reversed by the observer. (The observer could stop the apparent motion by continuing to reduce its temporal frequency but could not reverse the direction during a trial.)

During an individual trial the graphical elements in both bars had the same chromatic and luminance contrast; contrast was varied across trials. Four levels of chromatic and luminance contrast were combined factorially for a total of 16 CL contrasts. The four levels of chromatic contrast varied between the red and green primary colors (this is graphically illustrated for the CIELUV color space in Figure 2). The four levels of luminance contrast varied from no contrast to a contrast of 9 cd/m^2. The targeted levels of contrast are listed in Table 1A.

Three separate sets of stimuli were developed for the three experimental sessions by rotating the luminance contrast (LC) within levels of chromatic contrast (CC). For example, the three graphical elements for Luminance Contrast 3 (LC 3) in Set 1 had targeted

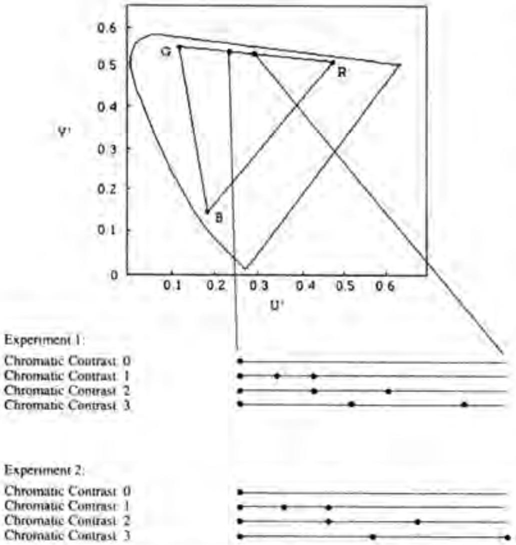

Figure 2. *Graphic representation of the chromatic contrast for Experiments 1 and 2. The expanded portion of the graph illustrates one sixth of the range between the red and green primaries. The dots on the lines illustrate the relative size of the chromatic contrast among the three graphical elements. For example, in the 0-level contrasts the three dots are superimposed, indicating that there was no chromatic contrast present.*

luminance values of 15, 10.5, and 6 cd/m^2. In Set 2 the targeted values were 10.5, 6, and 15 cd/m^2; in Set 3 the targeted values were 6, 15, and 10.5 cd/m^2.

The chromaticity coordinates and luminance contrasts were measured for each of the three repeating graphical elements in each of the 16 CL contrasts and the three sets. All measurements were made with a Minolta Chroma Meter (model CS101), which measured chromaticity in x and y coordinates (CIE) and luminance in cd/m^2. All chromaticity measurements were translated into the CIELUV u' and v' chromaticity coordinates using the formulas $u' = 4x/-2x + 12y + 3$ and $v' = 9y/-2x + 12y + 3$, as described in Merrifield and Silverstein (1986). Two analyses of these measurements were conducted to determine how well the obtained perceptual contrasts corresponded to the targeted contrasts.

The first analysis was for luminance contrast. The Michelson formula was used: $C = (L_{\max} - L_{\min})/2\ (\bar{L})$, where $L_{\max}$ is the maximum luminance, $L_{\min}$ is the minimum luminance, and $\bar{L}$ is the mean luminance. The luminance measurements for the three repeating graphical elements were compared to determine the maximum and minimum values. The resulting contrast values were then averaged across the three stimuli sets, and the results are listed in Table 2A. Averaging across the four levels of chromatic contrast reveals that the overall luminance contrasts were $C = 0.49\%$, 11.82%, 25.98%, and 43.30%. The same analysis was performed for the targeted luminance contrasts, and average values of $C = 0\%$, 11.1%, 25%, and 42.86% were obtained. Thus there is a good correspondence between the targeted and obtained luminance contrasts.

The second analysis was conducted to check chromatic contrast and to obtain an overall estimate of differences in perceptual salience. The CIELUV color difference equations, as described in Merrifield and Silverstein (1986, pp. 29–37), were used. The perceptual difference between two stimuli with small angular subtense is described by the equation $\Delta E^*_{\mathrm{SF}} = [(k_{\mathrm{L}}\ \Delta L^*)^2 + (k_{\mathrm{u}}\ \Delta U^*)^2 + (k_{\mathrm{v}}\ \Delta V^*)^2]^{1/2}$, in which:

$L^* = [116\ (Y/Yn)^{1/3}] - 16$; $U^* = 13\ [L^*\ (u' - u'n)]$; $V^* = 13\ [L^*\ (v' - v'n)]$;
$u' = 4x/[(-2x) + (12y) + 3]$; $v' = 9y/[(-2x) + (12y) + 3]$;
$k_{\mathrm{L}} = 0.2310$ (light/dark small-field correction factor); $k_{\mathrm{u}} = 0.0912$ (red/green small-field correction factor); $k_{\mathrm{v}} = 0.8150$ (violet/green-yellow small-field correction factor);
$u'n = 0.1978$ (1976 UCS u' coordinate of neutral chromatic point D65); $v'n = 0.4684$ (1976 UCS v' coordinate of neutral chromatic point D65); and
$Yn = 72.9$ (maximum display luminance in cd/m^2 measured by photometer);
$Y =$ luminance in cd/m^2 measured by photometer; $x =$ CIE x coordinate measured by

TABLE 1

Targeted Chromatic and Luminance Contrast between Repeating Graphical Elements

	Chromaticity Coordinates (u', v')			Luminance (cd/m^2)		
Element #	*1*	*2*	*3*	*1*	*2*	*3*
		A: Experiment 1				
Contrast 0	0.2097, 0.5454	0.2097, 0.5454	0.2097, 0.5454	15.0	15.0	15.0
Contrast 1	0.2097, 0.5454	0.2163, 0.5447	0.2229, 0.5440	15.0	13.5	12.0
Contrast 2	0.2097, 0.5454	0.2229, 0.5440	0.2360, 0.5425	15.0	12.0	9.0
Contrast 3	0.2097, 0.5454	0.2294, 0.5433	0.2492, 0.5411	15.0	10.5	6.0
		B: Experiment 2				
Set 1						
Contrast 0	0.1176, 0.5554	0.1176, 0.5554	0.1176, 0.5554	15.00	15.00	15.00
Contrast 1	0.1176, 0.5554	0.1253, 0.5546	0.1330, 0.5538	15.00	14.55	14.10
Contrast 2	0.1176, 0.5554	0.1330, 0.5538	0.1484, 0.5522	15.00	14.10	13.20
Contrast 3	0.1176, 0.5554	0.1407, 0.5530	0.1638, 0.5506	15.00	13.65	12.30
Set 2						
Contrast 0	0.1638, 0.5506	0.1638, 0.5506	0.1638, 0.5506	15.00	15.00	15.00
Contrast 1	0.1638, 0.5506	0.1715, 0.5498	0.1792, 0.5490	15.00	14.55	14.10
Contrast 2	0.1638, 0.5506	0.1792, 0.5490	0.1946, 0.5474	15.00	14.10	13.20
Contrast 3	0.1638, 0.5506	0.1869, 0.5482	0.2100, 0.5458	15.00	13.65	12.30
Set 3						
Contrast 0	0.2100, 0.5458	0.2100, 0.5458	0.2100, 0.5458	15.00	15.00	15.00
Contrast 1	0.2100, 0.5458	0.2177, 0.5450	0.2254, 0.5442	15.00	14.55	14.10
Contrast 2	0.2100, 0.5458	0.2254, 0.5442	0.2408, 0.5426	15.00	14.10	13.20
Contrast 3	0.2100, 0.5458	0.2331, 0.5434	0.2562, 0.5410	15.00	13.65	12.30
Set 4						
Contrast 0	0.2562, 0.5410	0.2562, 0.5410	0.2562, 0.5410	15.00	15.00	15.00
Contrast 1	0.2562, 0.5410	0.2639, 0.5402	0.2716, 0.5394	15.00	14.55	14.10
Contrast 2	0.2562, 0.5410	0.2716, 0.5394	0.2870, 0.5378	15.00	14.10	13.20
Contrast 3	0.2562, 0.5410	0.2793, 0.5386	0.3024, 0.5362	15.00	13.65	12.30
Set 5						
Contrast 0	0.3024, 0.5362	0.3024, 0.5362	0.3024, 0.5362	15.00	15.00	15.00
Contrast 1	0.3024, 0.5362	0.3101, 0.5354	0.3178, 0.5346	15.00	14.55	14.10
Contrast 2	0.3024, 0.5362	0.3178, 0.5346	0.3332, 0.5330	15.00	14.10	13.20
Contrast 3	0.3024, 0.5362	0.3255, 0.5338	0.3486, 0.5314	15.00	13.65	12.30

The contrasts between dimensions were combined factorially for 16 CL differences.

photometer; and y = CIE y coordinate measured by photometer.

A separate ΔE^*_{SF} value was calculated for each contrast within the three repeating graphical elements (i.e., Square 1 vs. Square 2, Square 1 vs. Square 3, and Square 2 vs. Square 3). The largest ΔE^*_{SF} values for each of the 16 CL differences in a stimulus set were then averaged across stimulus sets, and the results are shown in Table 2b. Values in the top row represent chromatic contrast alone; values in the leftmost column represent luminance contrast alone.

The same analysis was performed on the targeted measurements (Table 1A). The targeted ΔE^*_{SF} values for chromatic contrast were 0.0, 2.08, 4.15, and 6.23, whereas the obtained values were 0.09, 2.03, 4.38, and 6.59 (top row of Table 2B); the targeted values for luminance contrast were 0.0, 4.03, 8.8, and 14.8, whereas the obtained values were 0.09, 4.28, 9.20, and 14.85 (left column of Table 2B). Thus there is a good correspondence

TABLE 2

Average Luminance and Perceptual Differences for Experiment 1

Luminance Contrast	*Chromatic Contrast*			
	0	*1*	*2*	*3*
A: Average Luminance Contrast ($C = L_{max} - L_{min}/L_{max} + L_{min}$)				
0	0.00%	0.58%	0.46%	0.92%
1	11.95%	11.80%	11.92%	11.60%
2	26.39%	25.77%	25.63%	26.12%
3	43.43%	43.29%	43.28%	43.21%
B: Average Perceptual Differences (ΔE^*_{SF})				
	0	*1*	*2*	*3*
0	0.09	2.03	4.38	6.59
1	4.28	4.52	5.18	7.04
2	9.20	9.08	9.40	10.09
3	14.85	14.88	15.13	15.47

between the targeted and obtained chromatic contrast and ΔE^*_{SF} values.

There were limitations on the precision of these measurements. This is most evident in the LC 0/CC 0 measurements, where no perceptual differences should have existed. Because the exact same RGB values were used, the reported measurements indicate the existence of residual noise in the screen or photometer. A large contributor was the fact that above 10 cd/m^2 the luminance measurements had a resolution of only one decimal place.

Procedure. The observers were seated in an enclosed room with flat-black walls, and all ambient lighting was removed. The experiment was conducted during a three-day period with one experimental session per day. During a previous experiment the observers were provided with both a written and a verbal explanation of the task, including instructions to respond as accurately and quickly as possible.

A modified version of a standard psychophysical procedure (the method of adjustment) was used. The observer's task was to change the temporal frequency of the comparison bar to match the temporal frequency of the standard bar. The initial temporal frequency of the comparison bar was either higher (13.3 Hz) or lower (1.67 Hz) than that of the standard bar (either 5 or 10 Hz). The two initial rates for the comparison bar were interleaved randomly across trials. The first input by the observer increased or decreased the temporal frequency of the comparison bar by a predetermined increment of 1.67 Hz. From that point the size of the change in temporal frequency depended on both the size of the current increment and the direction of previous observer input. An observer input in the opposite direction from the previous input (a reversal) changed the temporal frequency by half the current increment. An observer input in the same direction as the previous input changed the temporal frequency by the current increment, unless the two previous observer inputs were in the same direction. In that case the change in temporal frequency was double the current increment.

After the eighth reversal a trial ended automatically. Although there was a lower limit on the temporal frequency of the comparison bar (0 Hz), there was no upper limit on the temporal frequency that could be demanded. Measures of accuracy and latency (accurate to 1/100 s) were obtained for each experimental trial. Observers were provided with feedback for accuracy but not for latency.

To summarize, in each of three experimental sessions (Days 1 through 3, within-subjects factor) an observer completed 64 trials: a factorial combination of the 16 chromaticity/luminance contrasts (four chromatic contrasts combined factorially with four luminance contrasts, within-subjects factors), the two directions of the comparison bar (left or right, within-subjects factor), and the two temporal frequencies for the standard bar (5 or 10 Hz, within-subjects factor). The order of these trials was determined randomly in each experimental session, and the order of stimulus sets was counterbalanced across observers.

RESULTS

Accuracy

When an observer increased the raw update rate of the comparison bar to a level that was greater than the refresh rate of the monitor (66 Hz), apparent forward motion, apparent backward motion, or a lack of apparent motion could be present. Thus all scores in which the temporal frequency of the comparison bar was greater than 22 Hz (corresponding to a raw update rate of 66 Hz) were dropped from the analyses.

Of the 768 total scores, 13 scores (1.69%) were removed using this criterion. An error magnitude score was obtained by averaging the temporal frequency (Hz) of the comparison bar before and after the eighth reversal, subtracting this value from the temporal frequency (Hz) of the standard bar, and taking the absolute value of the difference. Preliminary analyses indicated that the experimental session variable had no significant effect on matching performance. Thus the remaining scores were averaged across the three experimental sessions for a total of 64 scores per observer.

A 4 × 4 × 2 × 2 repeated-measures ANOVA was performed on these scores. The assumption of noncorrelation between repeated measures was checked by calculating the Greenhouse-Geisser estimate of epsilon. For effects in which this assumption was violated, the appropriate reduction in degrees of freedom was made to determine probability levels (for both ANOVA effects and post hoc comparisons). The main effects of chromaticity, $F(3,9) = 13.45$, $p < 0.01$, and luminance, $F(3,9) = 26.50$, $p < 0.02$, and the interaction effect between chromaticity and luminance, $F(9,27) = 9.56$, $p < 0.02$, were significant. All other effects were not significant.

The means for the main effects of both chromaticity and luminance are shown in Figure 3A. Supplemental F tests for luminance contrast (LC) revealed that performance with

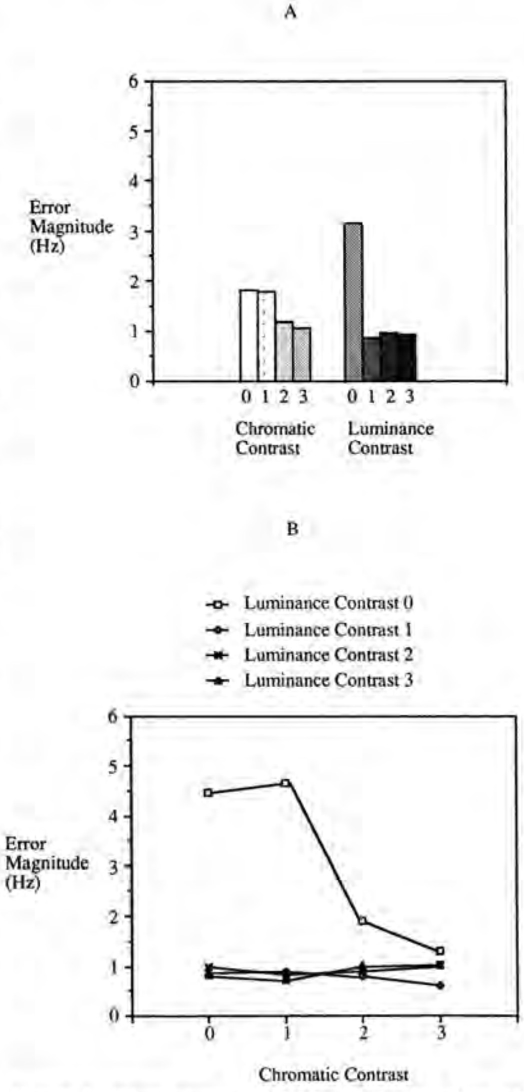

Figure 3. *Mean accuracy (Hz) for the main effects of chromatic and luminance contrast (A) and their interaction (B) in Experiment 1.*

Luminance Contrast 0 (LC 0) was significantly less accurate than with all other luminance contrasts, $F(1,9) = 57.22$, $p < 0.004$, $F(1,9) = 49.73$, $p < 0.005$, $F(1,9) = 51.63$, $p < 0.005$, whereas all other comparisons failed to reach significance. F tests for chromatic contrast (CC) indicated that the mean error magnitude for CC 0 was significantly less accurate than that for CC 2 or CC 3, $F(1,9) = 15.91$, $p < 0.02$, $F(1,9) = 24.36$, $p < 0.01$, and that accuracy for CC 1 was also significantly less than that for CC 2 or CC 3, $F(1,9) = 15.57$, $p < 0.02$, $F(1,9) = 23.94$, $p < 0.01$. All other comparisons failed to reach significance.

The significant interaction indicates that the quality of matching performance was dependent on both chromatic and luminance contrasts (see Figure 3B). F tests for simple interaction effects were conducted for all pairs of luminance contrasts (e.g., LC 0 vs. LC 1). These tests revealed that all simple interaction effects including LC 0 were significant, $F(3,27) = 16.14$, $p < 0.01$, $F(3,27) = 18.66$, $p < 0.01$, $F(3,27) = 21.70$, $p < 0.01$, but that all other simple interaction effects were not significant. Thus the overall interaction effect between chromaticity and luminance was attributable to the effects of chromatic contrast at LC 0. When no luminance contrast was available, observers' matching performance improved as chromatic contrast became larger.

Because the accuracy scores in the previous analyses were computed with absolute error rather than signed error, there was no consideration of response bias (i.e., consistently over- or underestimating rate). To check for response bias, the signed error scores were submitted to similar analyses. The results revealed a main effect for direction, $F(1,3) = 11.07$, $p < 0.05$, indicating that observers tended to overestimate rate when the graphical elements in the two bars were moving in the same direction (right to left, mean = 0.63 Hz) and to underestimate rate when the graphical elements were moving in the opposite direction (left to right, mean = −0.62). The results also revealed significant interaction effects of Chromaticity × Temporal Frequency, $F(3,9) = 9.94$, $p < 0.01$, Luminance × Temporal Frequency, $F(3,9) = 8.88$, $p < 0.05$, and Chromaticity × Luminance × Temporal Frequency, $F(9,27) = 9.38$, $p < 0.02$ (all other effects were nonsignificant).

Supplemental F tests revealed that for all three interaction effects, the response bias was a tendency to overestimate the slower temporal frequency and to underestimate the faster temporal frequency, and that this bias occurred only when sufficient chromatic or luminance contrast was not present. F tests were conducted to examine the simple interaction effects in the three-way interaction (all chromatic contrast and rate interactions were tested at each level of luminance contrast).

Significant interaction effects were found only in the LC 0 condition, and only when either of the two lower levels of chromatic contrast (bias present) was compared with either of the two higher levels of contrast (bias not present). Signed errors will not be considered further, given that bias was not found for either variable of primary interest and the measure of absolute error magnitude more directly highlights performance differences with respect to these variables.

Latency. A 4 × 4 × 2 × 2 repeated-measures ANOVA was performed on the latency scores. The analysis revealed no significant effects.

DISCUSSION

The results suggest that both luminance and chromatic contrast can be useful in producing apparent motion in animated mimic displays. The significant main effect for luminance contrast indicated that the accuracy of matching performance was improved significantly when any nonzero luminance contrast (12%, 26%, or 43%) was present. There was also a significant main effect for chromatic contrast, indicating that the accuracy of matching performance was improved significantly by the two higher levels of chromatic contrast (relative to the two lower levels). The significant interaction effect indicated that the accuracy of matching performance was dependent on both luminance and chromatic contrast. In particular, the interaction effect occurred only when no luminance contrast was present. Under these conditions, observers' performance improved as the level of chromatic contrast increased. These results suggest that chromatic contrast alone can be used to perform the rate-matching task accurately, provided that it is sufficiently large.

To summarize, although observers were able to use chromatic contrast to match the apparent motion of the two bars (when it was sufficiently large), it appears that luminance contrast was preferred. One interpretation of these results is that luminance contrast is more critical for the perception of motion than is chromatic contrast. However, an alternative explanation is that observers were simply using the information that was most salient perceptually. As Table 2B reveals, the range of luminance contrasts that were chosen was more discriminable than the range of chromatic contrasts (as defined by the CIELUV color difference equations). In Experiment 2 the luminance contrast was reduced and the chromatic contrast was enlarged to investigate this alternative explanation.

EXPERIMENT 2

Method

Subjects. Seven observers (5 male and 2 female) participated in the experiment and were paid $5.00 an hour. None of the observers participated in Experiment 1, but all had participated in a previous experiment (5 sessions of approximately 40 min). Their ages ranged from 20 to 25 years, and all had normal or normal-corrected vision with no color blindness deficiencies.

Apparatus. The apparatus was identical to that in the previous experiments.

Stimuli. All aspects of the stimuli remained the same as in Experiment 1, with the following exceptions. Rather than rotating luminance contrast within chromatic contrast, we developed five sets of chromatic contrast (see Table 1B). The largest chromatic contrast was increased to approximately one sixth of the line connecting the red-green primaries (see Figure 2). The largest luminance contrast was reduced to approximately 2.7 cd/m^2 (as opposed to 9 cd/m^2 in Experiment 1; see Table 1B).

The measurement of stimuli and the analyses performed on these measurements were exactly the same as in Experiment 1. The luminance contrasts for the 16 CL combinations, averaged across stimulus sets, are listed in Table 3A. The average luminance contrasts (across chromatic contrasts) were $C = 0.39\%$, 2.80%, 6.21%, and 9.79%, compared with the target values of $C = 0\%$, 3.1%, 6.4%, and 9.9%. The average ΔE^*_{SF} values (Table 3B) indicate that the relative contribution of chromatic and luminance contrast to overall perceptual salience was reversed relative to Experiment 1.

The targeted values for average chromatic contrast were 0.0, 2.43, 4.86, and 7.29, whereas the obtained values were 0.18, 2.58, 4.92, and 7.23 (top row of Table 3B). The targeted values for average luminance contrast were 0.0, 1.17, 2.38, and 3.66, whereas the obtained values were 0.18, 1.05, 2.28, and 3.42 (left column of Table 3B). As in Experiment 1, these analyses indicate that there was a good correspondence between targeted and obtained contrasts.

TABLE 3

Average Luminance and Perceptual Differences for Experiment 2

Luminance Contrast	*Chromatic Contrast*			
	0	*1*	*2*	*3*
	A: Average Luminance Contrast $(C = L_{max} - L_{min}/L_{max} + L_{min})$			
0	0.11%	0.22%	0.56%	0.67%
1	2.77%	3.01%	2.77%	2.66%
2	6.19%	6.21%	6.23%	6.22%
3	9.34%	9.76%	10.17%	9.88%
	B: Average Perceptual Differences (ΔE^*_{SF})			
	0	*1*	*2*	*3*
0	0.18	2.58	4.92	7.23
1	1.05	2.69	4.98	7.23
2	2.28	3.16	5.17	7.45
3	3.42	4.14	5.67	7.56

Procedure. The procedure was the same as that in the previous experiment, with two exceptions. First, testing was extended for a total of five experimental sessions. Second, the average initial difference in temporal frequency between the standard and comparison bars was reduced. Rather than the two initial frequencies that were used for the comparison bar in Experiment 1 (1.67 or 13.3 Hz), four initial frequencies were used (3.33, 6.67, 8.33, or 11.67 Hz).

RESULTS

Accuracy. As in Experiment 1, all scores in which the final temporal frequency of the comparison bar was greater than 22 Hz were not considered in the analyses. Of the 2240 total scores, 26 scores (1.16%) were removed using this criterion. Preliminary analyses indicated that the experimental session variable had no significant effect on performance, and scores were averaged across the five experimental sessions for a total of 64 scores per observer. A 4 × 4 × 2 × 2 repeated-measures ANOVA was performed on these scores.

The main effects of luminance, $F(3,18) = 7.43, p < 0.01$, chromaticity, $F(3,18) = 6.06, p < 0.02$, and temporal frequency, $F(1,6) = 19.49, p < 0.005$ were significant, as was the Chromaticity × Temporal Frequency × Direction interaction effect, $F(3,18) = 4.12, p < 0.05$. All other effects were nonsignificant. It should be mentioned that the interaction between luminance and chromatic contrast was significant initially, $F(9,54) = 2.41, p < 0.03$, but failed to reach significance when the degrees of freedom were adjusted for correlation of repeated measures ($p < 0.12$).

The means for the main effect of chromaticity and luminance are illustrated in Figure 4A, and the means for their interaction are illustrated in Figure 4B. Supplemental F tests for luminance contrast indicated that matching performance for LC 0 was significantly less accurate than that for all other luminance contrasts, $F(1,18) = 15.87, p < 0.004$, $F(1,18) = 17.03, p < 0.003$, $F(1,18) = 10.14, p < 0.02$, whereas all other comparisons were not significantly different. Similar F tests for chromatic contrast indicated that performance for CC 0 was significantly less accurate than that for CC 2 or CC 3, $F(1,18) = 8.25, p < 0.03$, $F(1,18) = 13.35, p < 0.01$, whereas performance for CC 1 was significantly less accurate than that for CC 3, $F(1,18) = 8.87, p < 0.02$. All other comparisons were nonsignificant. The main effect of temporal frequency indicated that when the graphical elements in the standard bar were moving at the slower rate (mean error magnitude = 1.14), observers were significantly more accurate than they were at the faster rate (mean = 1.79).

The means for the Chromaticity × Temporal Frequency × Direction interaction effect are illustrated in Figure 5. Supplemental F tests for the simple interaction effects

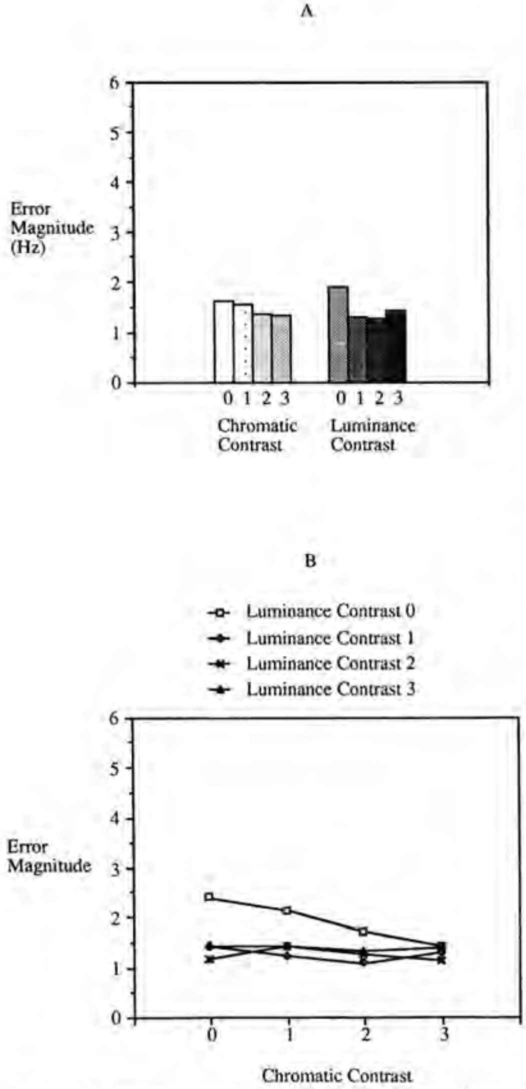

Figure 4. *Mean accuracy (Hz) for the main effects of chromatic and luminance contrast (A) and their interaction (B) in Experiment 2.*

between temporal frequency and direction were calculated for each level of chromatic contrast. These tests revealed that none of the four simple interaction effects reached statistical significance, $F(1,18) = 4.28$, $p < 0.07$; $F(1,18) = 2.36$, $p < 0.15$; $F(1,18) = 4.55$, $p < 0.07$; $F(1,18) = 1.20$, $p < 0.26$.

The simple main effects were also computed at each level of chromatic contrast. The simple main effects for temporal frequency were significant at all levels, $F(1,18) = 27.90$, $p < 0.001$, $F(1,18) = 32.26$, $p < 0.001$, $F(1,18) = 15.36$, $p < 0.01$, $F(1,18) = 28.00$, $p < 0.001$, indicating improved performance for the lower frequency. The simple main effects for direction were significant at CC 1, $F(1,18) = 9.74$, $p < 0.02$, and CC 2, $F(1,18) = 5.78$, $p < 0.05$. In both instances performance was significantly better when the direction of the comparison bar matched the direction of the standard bar (when the graphical elements were being shifted from the right to the left).

Latency. The 26 latency scores were not considered in the analysis; the remaining latency scores were averaged across experimental session. A 4 × 4 × 2 × 2 repeated-measures ANOVA was performed on these scores. The main effects of chromaticity, $F(3,18) = 11.25$, $p < 0.01$, luminance, $F(3,18) = 7.86$, $p < 0.03$, and the interaction effect between chromaticity and luminance, $F(9,54) = 9.01$, $p < 0.002$, were significant. All other effects were nonsignificant.

The means for the main effects of chromaticity and luminance are illustrated in Figure 6A. F tests for luminance indicated that performance for LC 0 was significantly faster than that for LC 1, LC 2, or LC 3, $F(1,18) = 12.17$, $p < 0.02$, $F(1,18) = 17.18$, $p < 0.02$, $F(1,18) = 16.94$, $p < 0.02$, whereas all other comparisons were not significant. F tests for chromaticity indicated that performance with CC 0 was significantly faster than for CC 2 or CC 3, $F(1,18) = 11.41$, $p < 0.02$, $F(1,18) = 29.95$, $p < 0.003$, whereas performance with CC 1 was significantly faster than that for CC 3, $F(1,18) = 15.95$, $p < 0.02$. All other comparisons were not significant.

The significant interaction indicates that

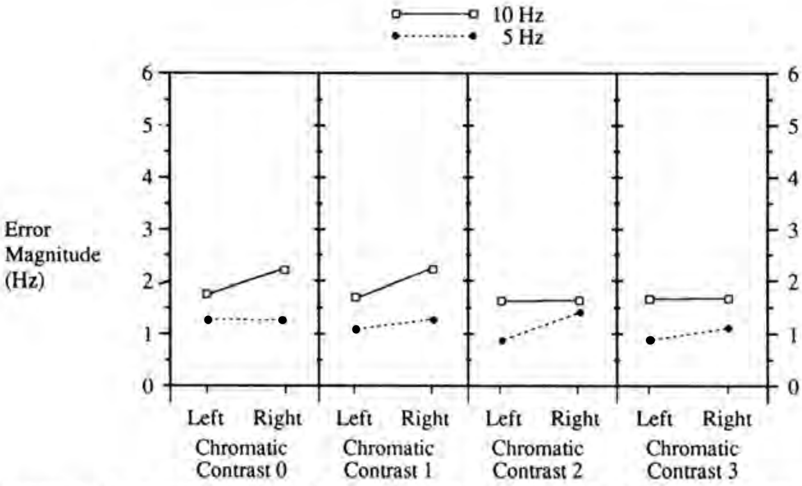

Figure 5. *Mean accuracy (Hz) for the chromatic contrast, temporal frequency, and direction interaction in Experiment 2.*

the latency of matching performance was dependent on both chromatic and luminance contrasts (see Figure 6B). *F* tests for simple interaction effects were conducted for all pairs of luminance contrasts (e.g., LC 0 vs. LC 1). These tests revealed that all simple interactions were significant when LC 0 was included, $F(3,54) = 10.15, p < 0.007$, $F(3,54) = 19.76, p < 0.0008$, $F(3,54) = 19.61, p < 0.0008$, whereas all simple interactions not involving LC 0 were nonsignificant. Thus these results indicate that the overall interaction effect between chromaticity and luminance was attributable to the simple interaction effect of chromatic contrast for LC 0. When there was no luminance contrast, the amount of time observers took to complete the matching task increased as chromatic contrast became larger.

DISCUSSION

One possible explanation for the results obtained in Experiment 1 is that observers were using the most salient information available, rather than a relative advantage for luminance contrast. Although the relative perceptual salience of luminance and chromatic contrast was reversed in Experiment 2, a similar pattern of results was obtained. Observers were able to match apparent motion accurately with any nonzero luminance contrast. As in Experiment 1, performance among all nonzero luminance contrasts was not significantly different, and all were significantly better than performance with zero luminance contrast (see Figure 4A). Thus the results suggest that a minimal level of luminance contrast is sufficient for performance of the task and that with the stairstep luminance profile this level lies at or below approximately 2.8%.

The accuracy of performance for chromatic contrast revealed a more positive pattern of results for Experiment 2 than for Experiment 1. In Experiment 2 the range of chromatic contrast was extended from slightly less than one-sixth of the red-green primary line to the full one-sixth range (see Figure 2). Observers' accuracy improved significantly with larger chromatic contrasts (CC 2 and CC 3) relative

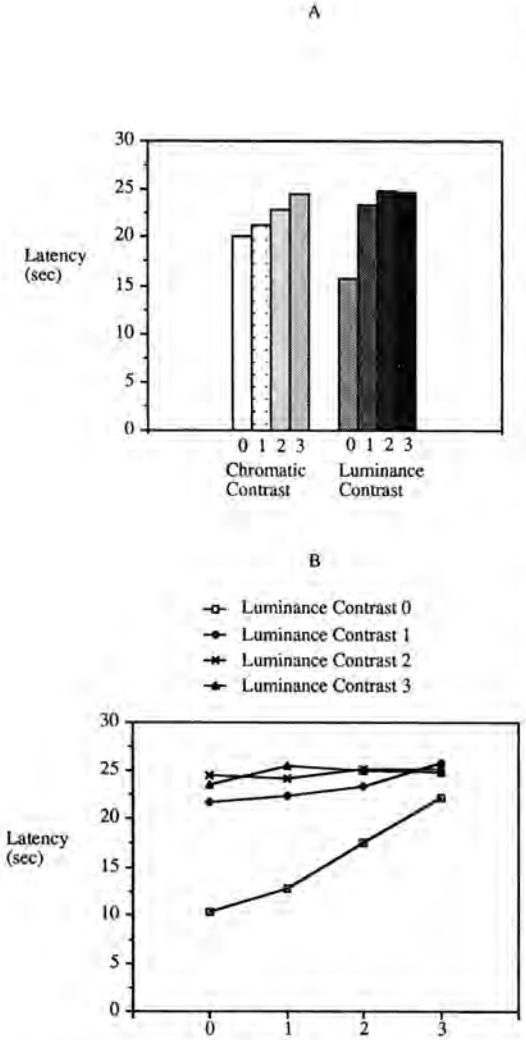

Figure 6. *Mean latency (s) for the main effects of chromatic and luminance contrast (A) and their interaction (B) in Experiment 2.*

to smaller (CC 1) or no (CC 0) chromatic contrast (see Figure 4A). In addition, the interaction effect between chromaticity and luminance failed to reach significance (originally $p < 0.02$, but with the Greenhouse-Geisser adjustments to degrees of freedom, $p < 0.12$). However, this adjustment is very conservative, and the pattern of results was similar to that obtained in Experiment 1 (see Figure 4B).

In contrast to Experiment 1, there was a significant effect for temporal frequency in Experiment 2: the accuracy of rate-matching performance was significantly better for 5 Hz than for 10 Hz. These results are consistent with previous research (e.g., Kelly, 1979) indicating that intermediate levels of temporal frequency produce performance that is superior to that produced with high or low temporal frequencies. One possible explanation for the lack of a significant effect in Experiment 1 is that the luminance contrast was so large that any costs associated with higher temporal frequency were offset.

There was also a significant Chromaticity × Temporal Frequency × Direction interaction effect (illustrated in Figure 5). The novel aspect of this result was the significant simple main effects for direction in the CC 1 and CC 2 experimental conditions. Observers were significantly more accurate when the graphical elements in the standard and comparison bars were moving in the same direction (right to left) than when they were moving in the opposite direction.

In contrast to Experiment 1, Experiment 2 revealed significant latency effects for luminance contrast, chromatic contrast, and their interactions. These results indicate that the amount of time to perform the task decreased significantly as contrast was reduced, suggesting a speed-accuracy trade-off. However, there is an alternative explanation.

With no differences in luminance or chromatic contrast (the zero/zero contrast condition), the task was impossible to complete accurately. A natural observer response was to alternate quickly between control inputs until the trial ended. Under these circumstances it is clear that the decrease in latency results from a simple lack of information required to complete the task, rather than a trade-off. Thus a reasonable interpretation of the reduced latency scores is that they reflect a natural observer response to experimental conditions in which the information necessary to complete the task was not available or degraded, rather than a speed-accuracy trade-off.

GENERAL DISCUSSION

The results of Experiments 1 and 2 suggest that both luminance and chromatic contrast can be used to encode apparent motion in animated mimic displays. However, the results also appear to indicate that chromatic contrast plays a secondary role relative to luminance contrast. It should be remembered that these results were obtained under conditions that favored chromatic contrast: the spatial displacement of the graphic elements and the observer seating distance ensured that long-range processes were operating. It was found that ΔE^*_{SF} values from 4 to 5 were required for chromatic contrast to produce significant differences in accuracy performance. Conversely, for luminance contrast a ΔE^*_{SF} value of less than 1 was sufficient to produce significant differences in performance.

These results suggest that observers were particularly sensitive to luminance contrast. In fact, an alternative explanation must be entertained for the improvements in performance attributed to chromatic contrast. It is possible that performance may have been facilitated by the small amounts of luminance contrast that accompanied increases in chromatic contrast, rather than by chromatic contrast per se. In LC 0 conditions the increase in luminance contrast ranged from 0.0% to 0.92% in Experiment 1 and from 0.11% to 0.67% in Experiment 2. In addition, it should be remembered that the estimates of luminance contrast shown in Tables 2 and 3 are based on the CIE photopic luminous efficiency function, which represents average levels of sensitivity across observers. The use of this function, instead of individualized sensitivity curves, underestimates the luminance contrast that is actually present. Thus the possibility that luminance contrast contributed to improved performance attributed to chromatic contrast cannot be ruled out.

In summary, it can be concluded that chromatic contrast should not be used as the primary method of encoding apparent motion in animated mimic displays. However, chromatic contrast can be used to convey important information about the underlying domain when used in combination with luminance contrast. Chromatic contrast can be used to signify different categories of information or resources in the domain (e.g., steam flow vs. feedwater flow in Figure 1A). It may also be effective in representing the qualitative changes that information or resources undergo as they traverse the system (e.g., the qualitative changes in the temperature of the coolant in the primary loop as it flows through the steam generator in Figure 1A).

As in all uses of color coding, the chromatic contrast in animated displays should reflect population stereotypes, and the salience of the contrast should reflect the relative importance of the information being conveyed. Above all, a large number of vibrant colors that produce "a grim parody of a video game" (Tufte, 1990, p. 88) should be avoided.

Additional Design Considerations

These experiments represent the first phase of a research program to investigate issues in the design of animated mimic displays. It is likely that the quality of the apparent motion produced by animated mimic displays can be improved by determining critical display variables (e.g., wave form, spatial frequency, temporal frequency, orientation, shape) and acceptable levels for these variables. Most of these variables were held constant in the present experiments and are worthy of additional consideration. Alternative methodological approaches might provide additional insights.

The results of the present experiment do provide some cause for concern. Although overall performance was high, on a small percentage of trials, large errors in accuracy occurred in both Experiments 1 and 2 (1.69% and 1.16%, respectively). An interesting perceptual effect may have contributed to these errors. Much like the "bistable" perceptual status of the Necker cube, it was possible to perceive flow in one direction and then, through a conscious shift in attention, to perceive flow in the opposite direction. The effect was sufficiently compelling that observers developed strategies to deal with the uncertainty that resulted. The most common strategy was to stop the apparent motion in the comparison bar and then slowly increase speed to determine direction. The small percentage of large errors may have been instances in which observers completed the task while focusing on the inappropriate direction.

One potential explanation of this perceptual effect is based on the nature of the wave forms that were used (stairstep), and insights from Fourier analysis. Fourier analysis maintains that any nonsinusoidal wave form can be described in terms of a combination of sinusoidal wave forms (harmonics) with specific spatial frequencies and amplitudes. There is some evidence that the visual system is, in fact, sensitive to these harmonics (Campbell and Robson, 1968; Sachs, Nachmias, and Robson, 1971). The direction, velocity, and salience of the apparent motion produced by each harmonic will depend on the fundamental frequency, amplitude, and phase shift of the wave form in the display. It is possible that sinusoidal harmonics produced apparent motion in both directions (see Bennett and Nagy, 1992, for a detailed discussion).

There are several potential design solutions. One possibility is to make the wave forms more sinusoidal-like, thus eliminating the majority of harmonics. A second possibility is to change the contour (shape) and borders of the graphical elements. Figure 7A represents the stimulus conditions that were investigated in the present experiment: the border between graphical elements was defined implicitly by luminance/chromatic contrast and the contours of the graphical elements remained constant (straight). Figures 7C and 7D represent graphical elements with contours that become more angled, or arrow-shaped, as the rate of flow increases (a medium flow from left to right is illustrated). Figures 7B and 7D illustrate graphical elements with borders that are defined explicitly with a line, rather than implicitly by perceptual contrast. In addition to providing an explicit indication of the direction of flow, contours provide a redundant coding for temporal frequency. (See Bennett and Madigan, in press, for an empirical evaluation of this design alternative.)

One final note concerns the limitations of the experimental methodology that was used in the present experiment. The method of adjustment allows the measurement of differential or absolute sensitivity. That is, it can measure how well an observer can make discriminations on the basis of changes in stimulus energy within a perceptual dimension. However, the method of adjustment cannot provide direct information about the

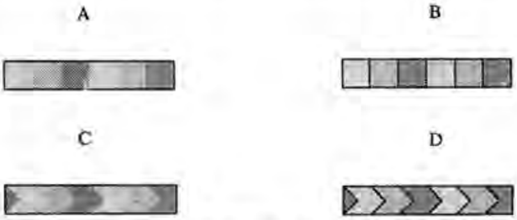

Figure 7. *Redundant coding of rate and direction of flow through contours (straight: A and B; angled: C and D) and borders (implicit: A and C; explicit: B and D).*

relationship between changes in stimulus energy and the corresponding changes in the psychological representation (i.e., sensation). Alternative experimental methodologies (e.g., magnitude estimation) will be required to measure this relationship directly.

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