CRITIQUE AND RESPONSE

Evaluation of Alternative Waveforms for Animated Mimic Displays

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Animated mimic displays can be used to present system information regarding physical form, function, and causality. However, a potential limitation in current designs has been identified: the presence of ambiguous apparent motion. Two theoretical explanations of ambiguous apparent motion are discussed (Fourier and correspondence hypotheses). Two alternative designs (stair-step and approximate sinusoid luminance waveforms) were evaluated. The velocity matches obtained in Experiment 1 indicate that the sinusoidal waveform produced significantly better performance for both accuracy and latency than the stair-step waveform. The velocity estimates obtained in Experiment 2 indicate that ambiguous apparent motion was not visible with the sinusoidal waveform, but was with the stair-step waveform. One of the two hypotheses (correspondence) provides a reasonable fit with the obtained velocity estimates. A fundamental goal in the design of animated mimic displays is to provide unambiguous mappings between perceived velocity and actual flow rates. Critical factors in design (e.g., waveform, chromatic/luminance contrast, spatial/temporal frequency) are discussed. Actual or potential applications of this research include the design of more effective animated mimic displays.

INTRODUCTION

Advances in computer technology have given system designers powerful tools that can be used to improve the quality of overall system performance. One such tool is graphics display technology, which can be used to improve decision making and problem solving through the provision of alternative conceptual perspectives or "views" of an underlying system. For example, operators must often collect and integrate scattered data that testify about higher-level goals, properties, and constraints. Properly designed configural displays (sometimes referred to as *object displays*) will assist the individual in completing these tasks (e.g., Bennett, Nagy, & Flach, 1997). In addition, observers must consider the physical characteristics of a system.

Displays that are used to represent this type of system information are often referred to as *mimic displays,* presumably because they mimic the physical structure of the system (e.g., Hawkins, Reising, & Gilmore, 1983a, 1983b; Hollan, Hutchins, McCandless, Rosenstein, & Weitzman, 1987; Hollan, Hutchins, & Weitzman, 1984). An example from Hawkins et al. (1983b) is provided in Figure 1. This mimic display provides a schematic of the fuel system in an advanced fighter aircraft, including the physical location of each tank, the level of fuel within a tank, the physical connections between tanks, and the associated valves to control flow.

In terms of the Rasmussen, Pejtersen, and Goodstein (1994) abstraction hierarchy, mimic displays provide information at the level of "physical processes and activities." This "is the level at which physically limiting properties are represented and at which causes of malfunctions are typically identified. Physical changes in components have functional consequences that propagate up through the levels of abstraction"

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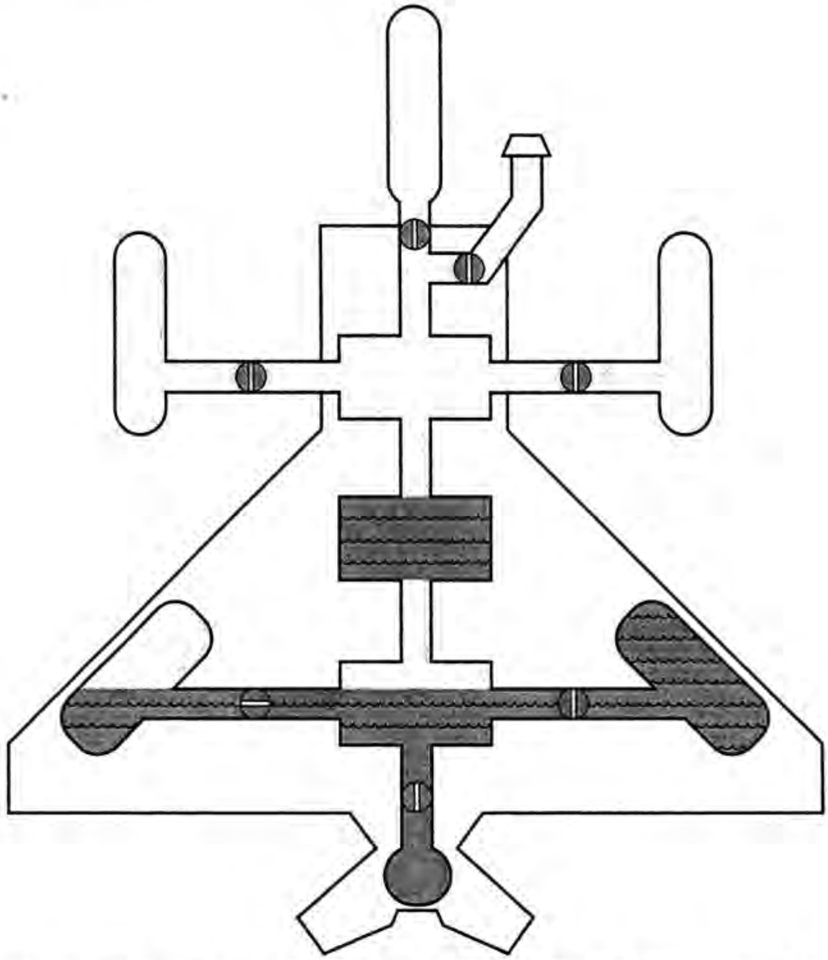


Figure 1. A mimic display adapted from Hawkins et al. (1983b). This fuel system status display includes a schematic outline of a fighter aircraft, fuel tanks, the level of fuel in each tank, transfer connections, and transfer valves. (Courtesy of the U.S. Air Force.)

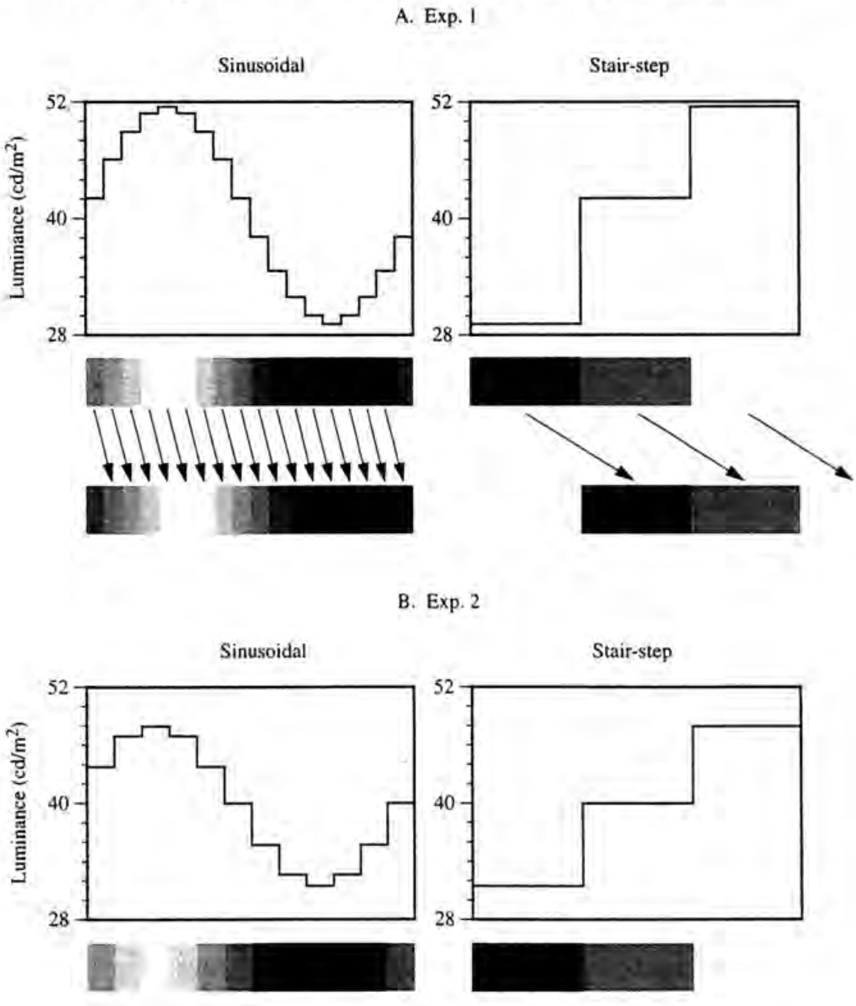
(Rasmussen, 1986, p. 17). Thus a potential benefit of mimic displays is the provision of support for fault detection and compensation tasks. These tasks include (a) detecting the fault; (b) identifying the type, location, and consequences of the fault; (c) identifying alternative resources that can be used to correct the fault; and (d) compensating for the fault by completing the required control inputs.

The potential benefits are apparent in the following example using the system depicted in Figure 1. To maintain the proper aerodynamics of an aircraft with multiple fuel tanks, the total amount of fuel within the system must be distributed among the various tanks appropriately. Imagine that there is a stuck valve in this system, causing the center of gravity to change and therefore impairing flight and maneuverability. The mimic display represents information that the pilot could use to identify the type of fault (i.e., stuck valve), the alternative resources (e.g., alternative tank or tanks and appropriate flow paths for rerouting fuel), and the control inputs that could be used to compensate for the fault (e.g., manually opening and closing the appropriate valves in the alternative flow path at the appropriate times).

One potential improvement in the design of mimic displays is to provide a direct (analogical) representation of flow rates. Although static mimic displays provide information about the physical structure of the system, they do not testify directly about the flow of information or resources among system components. Instead, this information must be obtained from analog meters or digital displays or must be assumed from the position of associated controls. A computationally efficient approach to representing this information directly is the color-table animation technique (Mulligan & Stone, 1989; Shoup, 1979). The perceptual characteristics of adjacent graphical elements in a display are translated (i.e., moved) so that they produce apparent motion. This process is represented graphically by the two pairs of shaded bars in Figure 2a. The top bars represent each waveform prior to an update, the bottom bars represent each waveform after an update, and the arrows pointing down and to the right represent a one-element translation from left to right.

A research program was initiated to identify the factors that are critical for the accurate perception of apparent motion in animated mimic displays (Bennett, 1993; Bennett & Madigan, 1994; Bennett & Nagy, 1996). We began our investigations with a display configuration based on the design illustrated in the STEAMER publications (Hollan et al., 1984, 1987). A critical aspect of this design is the stair-step waveform that was employed: three graphical elements with different levels of luminance contrast. (A schematic representation is provided in the right-hand graphs of Figures 2a and 2b.) Bennett (1993) varied the amount of luminance

Figure 2. The waveforms used in Experiments 1 and 2. (A) The luminance profiles of the approximate sinusoid waveform (left) and the stair-step waveform (right) in Experiment 1. The graphical depictions under the luminance profiles illustrate how the color table animation technique produced apparent motion. The two bars represent the display before (top) and after (bottom) an update to the screen. The arrows indicate the physical displacement, or translation, of the perceptual characteristics of the graphical elements (in this case, by one element from left to right). (B) The two waveforms used in Experiment 2.



and chromatic contrast among the three graphical elements of the repeating waveform using this design; Bennett & Nagy (1996) varied the spatial frequency, temporal frequency, and luminance contrast of the stair-step waveform. Both studies produced evidence that this design was less than optimal. Bennett (1993) summarized these concerns:

> Although overall performance was quite 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 "bi-stable" 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 where observers completed the task while focusing on the inappropriate direction. (p. 690)

Bennett & Nagy (1996) described a theoretical interpretation of this bidirectional motion based on insights from Fourier's theorem. In part, Fourier's theorem maintains that any waveform can be analyzed as a set of sinusoid waves, or harmonics. There is a fair amount of evidence that the visual system performs a similar analysis (Campbell & Robson, 1968; Kelly, 1972; Sachs, Nachmias, & Robson, 1971). Thus the *Fourier hypothesis* explains the bidirectional apparent motion in the following manner: During each update cycle, the perceptual characteristics of the graphical elements were translated by one graphical element (see the right-hand graph in Figure 2a). This introduces a one-third phase shift for the fundamental frequency (and apparent motion in the same direction as the physical update). However, this same physical update introduces a two-thirds phase shift for the second harmonic (and apparent motion in the opposite direction at a different velocity). Thus observers may have been able to see bidirectional motion by shifting attention between the fundamental and second harmonics (see Bennett & Nagy, 1996, for a more detailed discussion).

An alternative interpretation of the bidirectional apparent motion will be referred to as the *correspondence hypothesis* (Ullman, 1979). Anstis (1986, p. 16) describes the critical aspects of this hypothesis: "If two pictures are presented in rapid succession to the same retinal area AM [apparent motion] will be seen between corresponding features of the two pictures. The question is, How does the visual system know, or decide, which features are to be placed in correspondence?" From this perspective, bidirectional apparent motion might be perceived with these displays if two different sets of correspondences between visual features exist simultaneously, both of which can be interpreted by (i.e., are acceptable to) the visual system.

The correspondence explanation of the bidirectional motion in animated mimic displays is illustrated in Figure 3. The visual features in the stair-step waveform (Figure 3a) are represented before (top bar) and after (bottom bar) a physical update of the display from left to right. In one correspondence set, the visual features could be perceived as being translated in space by a distance corresponding to the width of one element in the direction of the physical update (illustrated by the arrows pointing down and from left to right). In the second correspondence set, the visual features could be perceived to be translated by the width of two elements in the opposite direction of the physical update (illustrated by the arrows pointing down and from right to left). Thus the correspondence hypothesis explains bidirectional apparent motion as the shifting of visual attention between alternative sets of correspondences.

Two experiments were conducted to identify factors that may reduce the occurrence of bidirectional apparent motion and improve the quality of perceived motion. Two display designs were evaluated: the stair-step waveform described previously and a waveform containing a luminance profile that approximated a sine wave (see the left graph in Figure 2a). Both hypotheses of bidirectional apparent motion predict that performance should be improved with the sinusoidal waveform. The

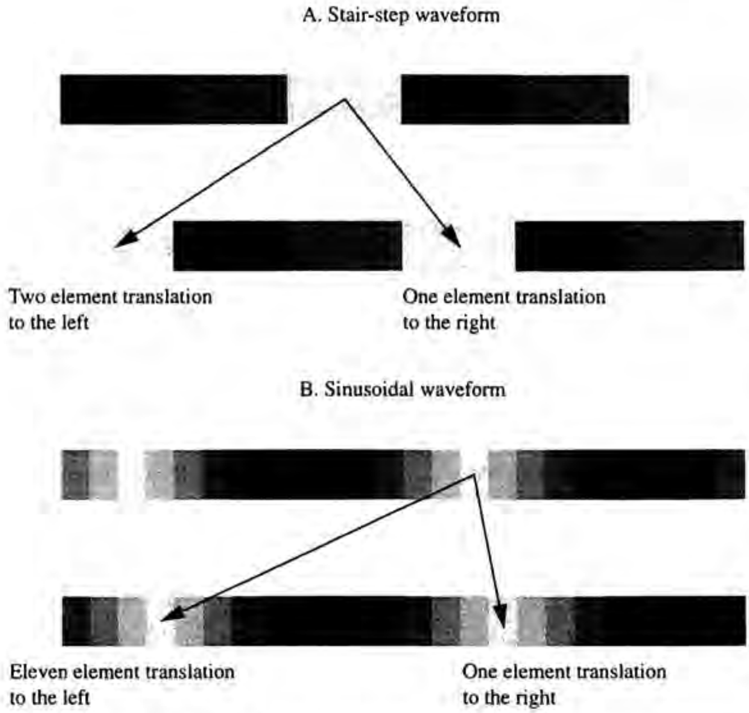


Figure 3. A graphical representation of the correspondence hypothesis of bidirectional apparent motion. (A) Alternative correspondence sets for the stair-step waveform. The top and bottom bars represent the visual appearance of the waveform before and after a one-element translation from left to right (L–R). One correspondence set (arrow pointing down and to the right) would produce apparent motion that is in the same direction as the physical translation: The graphical elements would be perceived as moving by one element from the left to the right. The second correspondence set (arrow pointing down and to the left) produces apparent motion in the opposite direction: The graphical elements would be perceived as moving by two elements from the right to left (R–L). (B) Alternative correspondence sets for the sinusoidal waveform.

visibility of additional harmonics should be reduced (Fourier), or the alternative correspondences should be more difficult to interpret (correspondence).

In the first experiment the two designs were evaluated using a variation of the method of adjustment. Two animated bars were presented (with the same waveform), and observers changed the velocity of apparent motion in one (the comparison bar) to match the velocity in the second (the standard bar). This methodology allows an assessment of the quality of apparent motion produced by the two designs: better rate-matching performance can be interpreted as evidence for better apparent motion (and better display design). However, only indirect evidence regarding the presence of bidirectional motion is available (i.e., it must be inferred from lower levels of performance).

In Experiment 2 the absolute magnitude estimation methodology (Stevens, 1956, 1958) was used. Observers were shown a single bar (containing one of the waveforms) and were required to provide estimates of velocity in both the same and the opposite direction of the physical update. This methodology provides a direct test for the presence of bidirectional motion and a direct test for predictions of perceived velocity derived from the two theoretical interpretations outlined previously.

EXPERIMENT 1

Method

Participants. Eight observers (four men and four women) participated in the experiment and were paid $5.00/hr. Their ages ranged from 20 to 29 years, and all had normal or normal-corrected vision.

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 GDM1604-15) 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. A head/chin rest (Lafayette Instruments, model 14300) was used.

Stimuli. Two horizontal bars were presented on a medium-grey background (u' = .2027, v' = .4739, cd/m^2 = 3.70). Two waveforms (sinusoidal, stair-step; see Figure 2a) were used; during a trial both bars had the same waveform. The sinusoidal waveform contained 144 graphical elements: 18 levels of luminance contrast approximating a sinusoid function that repeated 8 times. The stair-step waveform contained 24 graphical elements: 3 levels of luminance contrast in a stair-step function that repeated 8 times.

The lower bar was the "standard" bar. Apparent motion was produced by shifting the perceptual characteristics of the graphical elements to produce a velocity of 2.54°/s. To produce this velocity, we shifted the perceptual characteristics of the graphical elements in the sinusoidal waveform at a raw update rate of 32.94 Hz (because there were 18 elements in a cycle). For the stair-step waveform the update rate was 5.49 Hz (because there were 3 elements in a cycle).

The upper bar was the "comparison" bar, and its velocity was controlled by the observer. At the beginning of a trial, the velocity of the comparison bar was 0.00°, 0.72°, 1.46°, 2.18°, 2.92°, 3.64°, 4.36°, or 5.10°/s. The physical animation of both bars could occur either from left to right (L–R) or right to left (R–L).

Each bar was 14.63 cm wide and 0.76 cm high. The bars were separated vertically by a distance of 10.16 cm and centered on the screen. The viewing distance was maintained at 75 cm through the use of a head/chin rest. Thus each bar subtended a visual angle of 11.04° horizontally and 34.93 arc min vertically; the distance between the bars subtended a visual angle of 7.71°. For the sinusoidal waveform, each graphical element was 0.10 cm wide and subtended a visual angle of 4.58 arc min. For the stair-step waveform, each graphical element was 0.61 cm wide and subtended a visual angle of 27.96 arc min. One cycle of either waveform subtended a visual angle of 1.40° and had a fundamental spatial frequency of 0.72 cycles/°.

Contrast was measured with a Minolta Chroma Meter (model CS 101). The measured luminance values of the 18 repeating graphical elements in the sinusoidal waveform were 42.2, 46.2, 49.1, 51.0, 51.8, 51.0, 49.1, 46.2, 42.2, 38.3, 34.9, 32.1, 30.3, 29.4, 30.3, 32.1, 34.9, and 38.3 cd/m^2. The luminance contrast was calculated using the Michelson formula, $C = (L_{max} - L_{min})/2\ (\bar{L})$, where L_{max} is the largest of the measured luminance values, L_{min} is the smallest, and $\bar{L}$ is their mean. The contrast was 27.59%. The three graphical elements with the largest (51.8 cd/m^2), smallest (29.4 cd/m^2), and a medium (42.2 cd/m^2) luminance contrast were used in the stair-step waveform. The chromatic contrast of the graphical elements was approximately equal, with average values of u' = .1889 and v' = .4604 (CIELUV chromaticity coordinates).

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

A variation of a standard psychophysical procedure (the method of adjustment) was used. The observer's task was to change the velocity of the comparison bar to produce perceived velocities that matched that of the standard bar. The initial velocity of the comparison bar (0.00°, 0.72°, 1.46°, 2.18°, 2.92°, 3.64°, 4.36°, or 5.10°/s) was either higher or lower than that of the standard bar (2.54°/s). The eight initial velocities for the comparison bar were interleaved randomly across trials. The first input by the observer increased or decreased the velocity of the comparison bar by a predetermined value of 2.32°/s. Subsequent values depended on both the size of the current value and the direction of previous observer input. Observer input in the opposite direction from the previous input (a reversal) changed the velocity by half the current value. Observer input in the same direction as the previous input changed the velocity by the current value, unless the two previous observer inputs were in the same direction. In this case the change in velocity was double the current value.

The velocity of the comparison bar was limited to rates in which the associated temporal frequency did not exceed the maximum refresh rate of the monitor (66 Hz). An observer initiated a trial by clicking on a start button and could end the trial at any point by clicking on a stop button. Measures of accuracy and latency (accurate to 0.01 s) were obtained for each experimental trial. Observers were provided with feedback for both accuracy and latency.

To summarize, in each of five experimental sessions (Days 1–5) an observer completed 64 trials: a factorial combination of (a) waveform (sinusoidal or stair-step), (b) direction of the comparison bar (L–R or R–L), (c) direction of the standard bar (L–R or R–L), and (d) the initial velocity of the comparison bar (0.00°, 0.72°, 1.46°, 2.18°, 2.92°, 3.64°, 4.36°, or 5.10°/s).

RESULTS

In both of the ensuing analyses, outliers were removed using standardized deviate statistics (Barnett & Lewis, 1984; Lovie, 1986; Ratcliff, 1993). The test is described in Lovie (1986, pp. 55–56): $T_1 = (x_n - \bar{x})/s$, where $x_{(n)}$ is a particular observation (one of n observations), $\bar{x}$ is the mean of those observations, and s is the standard deviation of those observations. If a match failed for either accuracy or latency, the entire response was not considered. Of the 2560 matches that were administered, 63 were discarded (2.46%); Wilcoxon signed ranks tests revealed that the distribution was random.

Accuracy. An error magnitude score was obtained by taking the absolute value of the difference between the velocity of the comparison and standard bars. These scores were averaged across the initial velocity of the comparison bar and the experimental session. A 2 × 2 × 2 repeated-measures analysis of variance (ANOVA) was performed on these scores. The main effect of waveform was significant, $F(1, 7) = 19.69$, $p < .004$. The two-way interaction between the waveform and the direction of the comparison bar, $F(1, 7) = 10.94$, $p < .02$, and the three-way interaction between the waveform, the direction of the standard bar and the direction of the comparison bar were significant, $F(1, 7) = 7.17$, $p < .04$. No other effects were significant.

The means for the three-way interaction are illustrated in Figure 4a. Supplemental F tests were computed to compare performance between waveforms. When the apparent motions of the two bars were in the same direction, the sine wave produced significantly better performance: R–L R–L, $F(1, 7) = 12.90$, $p < .009$; L–R L–R, $F(1, 7) = 44.36$, $p < .0003$. When the comparison and standard bars were in the opposite direction, the sine wave produced significantly better performance for one of the two contrasts; comparison R–L, standard L–R, $F(1, 7) = 8.84$, $p < .03$.

Latency. A similar 2 × 2 × 2 repeated-measures ANOVA was performed on the averaged latency scores. The main effects of waveform, $F(1, 7) = 7.58$, $p < .03$, and direction of comparison bar, $F(1, 7) = 6.62$, $p < .04$, were significant. The three-way interaction among waveform, direction of the standard bar, and direction of the comparison bar was significant, $F(1, 7) = 16.46$, $p < .005$. All other effects were not significant.

The means for the three-way interaction are illustrated in Figure 4b. Supplemental contrasts revealed that latency was significantly better for the sinusoidal waveform when the apparent motion of the comparison bar was in the same direction as the standard bar; comparison R–L, standard R–L, $F(1, 7) = 10.59$, $p < .02$; comparison L–R, standard L–R, $F(1, 7) = 17.07$, $p < .005$. When the comparison and standard bars were in opposite directions, the sine wave produced significantly better performance in one of the two contrasts; comparison L–R, standard R–L, $F(1, 7) = 8.48$, $p < .03$.

DISCUSSION

The results of Experiment 1 indicate that the approximate sinusoid waveform produced superior performance at the velocity-matching task. The significant three-way interactions indicated that performance was dependent on the waveform as well as the direction of the

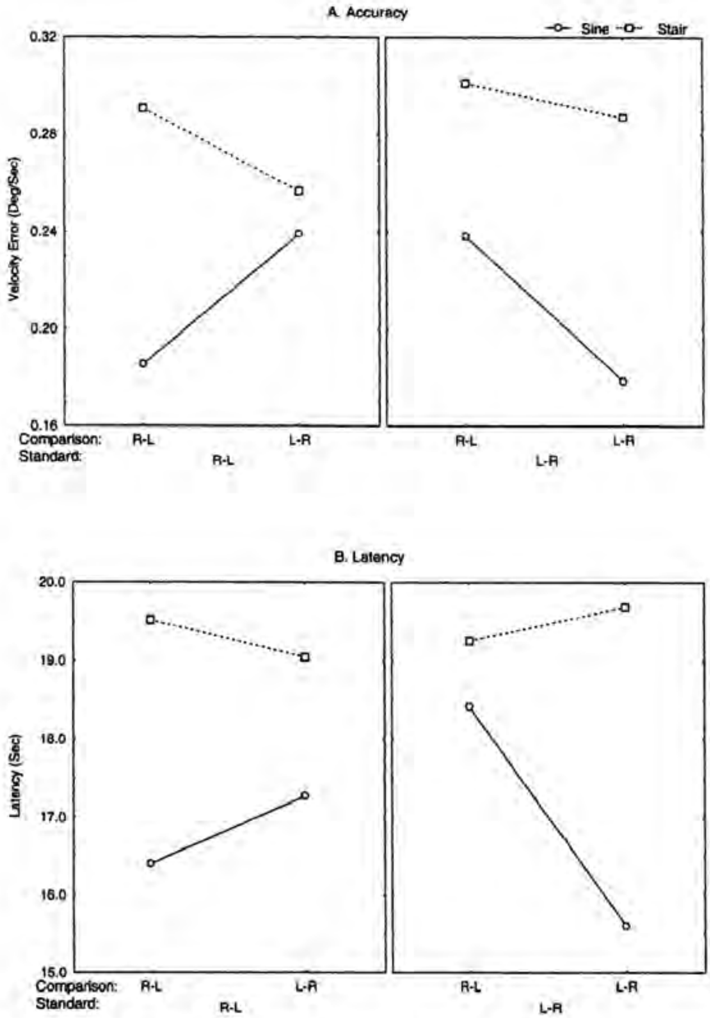


Figure 4. Means associated with the significant three-way interaction effects (waveform by direction of comparison bar by direction of standard bar) for the velocity-matching task in Experiment 1. (A) Accuracy. (B) Latency.

standard and comparison bars (see Figure 4). When the apparent motions of these two bars were in the same direction, observers were able to complete the velocity-matching task more effectively with the sinusoidal waveform than with the stair-step waveform. All four contrasts directly comparing performance (the far right and left means in Figure 4) were significant.

The performance advantages were still present when the apparent motions of the two bars were in opposite directions. For both accuracy and latency, performance was always better with the sine waveform (the inner means in Figure 4). Two of the four direct comparisons between waveforms were statistically significant under these experimental conditions. These results are interpreted as a clear indication that the sinusoidal waveform produced higher-quality apparent motion than did the stair-step waveform.

Although the sinusoidal waveform is a preferable design option, a better understanding of the psychological mechanisms and factors in technology or design that are responsible for the phenomenon of bidirectional apparent motion is critical. Uncertainties regarding both the direction and the velocity of flow that is being depicted will be unacceptable in real-world displays. The methodology used in Experiment 1 (method of adjustment) does not provide direct insights regarding bidirectional apparent motion. In Experiment 2 an alternative methodology was used to test directly for its presence and to compare two hypotheses regarding its origin. Classic magnitude estimation methodology requires participants to estimate the magnitude of a comparison stimulus relative to a standard provided by the experimenter. In a variation of this methodology, absolute magnitude estimation (AME), observers are not provided a standard and are therefore free to establish their own ranges of possible values (Stevens, 1956, 1958). AME allows a direct measure of the magnitude of apparent motion while avoiding potential magnitude biases (Gescheider & Hughson, 1991); it was used in Experiment 2. A brief summary of the experimental design, the two hypotheses regarding bidirectional apparent motion, and the predictions of perceived velocity generated from these hypotheses will be provided.

In Experiment 2, observers were presented with a single bar that was animated at one of five velocities and they were asked to provide an estimate of velocity magnitude. Both a stair-step and an approximate sinusoid waveform (see Figure 2b) were used. The physical updates to this bar (see Figure 2a) occurred in only one direction for each trial (either L–R or R–L). Similarly, observers provided an estimate of velocity magnitude in only one direction (either L–R or R–L).

The term *physical direction* will be used to refer to the direction of the physical translation of the graphical elements in the display (i.e., in Figure 2a the physical direction is L–R). The term *subjective direction* will be used to refer to the direction of motion that observers were asked to estimate. In half of all experimental trials the physical direction and the subjective direction were the same (e.g., R–L physical direction, R–L subjective direction), and in half they were different (e.g., R–L physical direction, L–R subjective direction). The term *consistent* will be used to refer to the former type of trial and *inconsistent* will be used to refer to the latter. Note that the inconsistent trials were specifically designed to test for the occurrence of bidirectional motion.

The predicted estimates of velocity derived from the Fourier hypothesis will be described first. This hypothesis maintains that bidirectional apparent motion results from the observer's ability to perceive (and shift attention among) multiple sinusoidal harmonics associated with a waveform. A Fourier analysis was performed on the two waveforms illustrated in Figure 2b to determine the physical characteristics of these harmonics and to develop appropriate stimuli for the experiment. Table 1 provides the results of this analysis in the context of the experimental manipulations.

The Fourier hypothesis predicts that apparent motion will be associated with the fundamental frequency (first harmonic – the most visible harmonic) when the physical direction and the subjective direction are consistent. Table 1 indicates that all key parameters for the stair-step waveform (Table 1, row A) and the sinusoidal waveform (Table 1, row C) are identical under these conditions. Therefore, no differences in estimates of apparent motion for the waveforms are predicted. Figure 5 provides a graphic illustration of the predicted estimates derived from the two hypotheses under all experimental conditions. The Fourier predictions for consistent directions are represented by the solid lines with circle symbols in Figure 5a (stair-step waveform) and Figure 5b (sinusoidal waveform).

We conducted the test for bidirectional motion when an inconsistent relationship existed between the physical and subjective directions of motion. The Fourier hypothesis maintains that bidirectional apparent motion occurs because observers can perceive additional harmonics that appear to move in the opposite direction of a physical update (caused by the apparent phase shift of the harmonic introduced by the physical update). Thus the visual feature most likely to be responsible for bidirectional apparent motion is the second most visible harmonic of the waveform.

As rows E and G of Table 1 indicate, the perceptual characteristics of this harmonic are different for the two waveforms, and different velocity estimates are predicted. For the stair-step waveform, the next most visible harmonic is the second harmonic (Table l, row E). The spatial frequency of this harmonic is increased by a factor of two, relative to the first harmonic (Table l, row A). As a result, the prediction of perceived velocity in the opposite direction is decreased by a factor of two (Figure 5a,

TABLE 1: Critical Waveform Characteristics and Predicted Velocity Estimates Derived from Alternative Hypotheses of Ambiguous Apparent Motion

	Luminance Profile	Hypothesis	Visual Feature	Luminance Contrast (*C*; Michelson %)	Spatial Frequency (cycles/°)	Temporal Frequency (cycles/s)	Velocity (°/s)
			Subjective Direction: Left to Right (L–R, Consistent)				
A	Stair step	Fourier	1st harmonic (F)	19.44	1.43	5.00	3.49
B	Stair step	Correspondence	1-element translation	20.31	1.43	5.00	3.49
C	Sinusoidal	Fourier	1st harmonic (F)	19.44	1.43	5.00	3.49
D	Sinusoidal	Correspondence	1-element translation	20.32	1.43	5.00	3.49
			Subjective Direction: Right to Left (R–L, Inconsistent)				
E	Stair step	Fourier	2nd harmonic	9.72	2.86	5.00	1.75+
F	Stair step	Correspondence	2-element translation	20.31	1.43	10.00	6.99
G	Sinusoidal	Fourier	11th harmonic	1.77	15.75	5.00	0.32
H	Sinusoidal	Correspondence	11-element translation	20.32	1.43	55.00	38.42

Note: Physical direction in all cases is left to right (L–R)

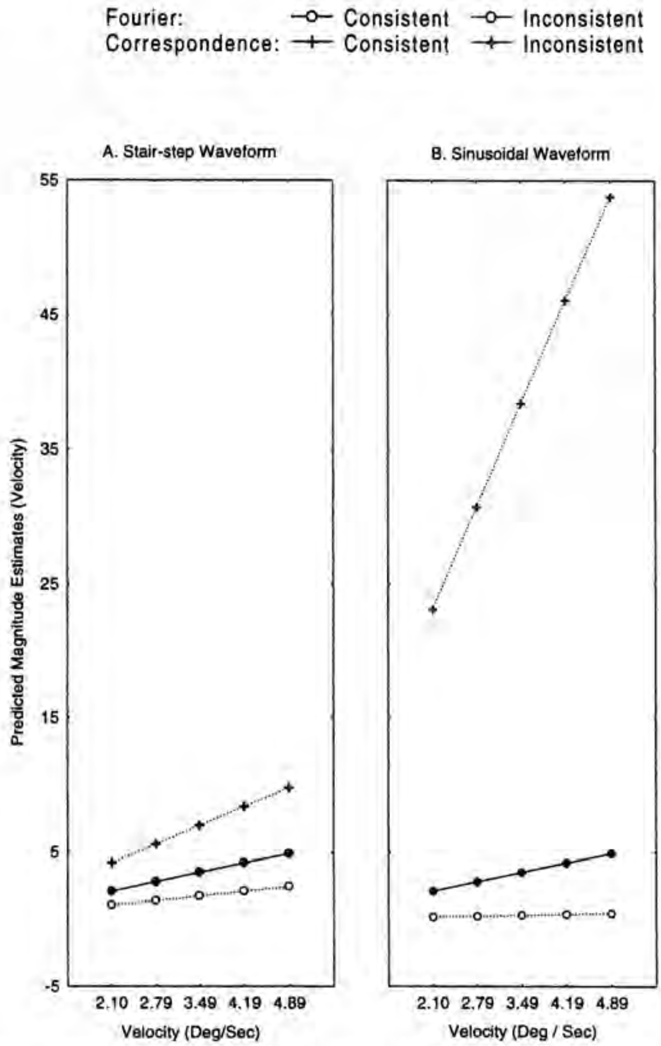


Figure 5. Predicted magnitude estimates of velocity (°/s) for various conditions of Experiment 2. (A) Predicted velocities for the stair-step waveform. Predictions derived from the Fourier hypothesis are represented by the open circle symbols; those derived from the correspondence hypothesis are represented by the cross symbols. Predictions for consistent directions (e.g., physical animation from left to right, L–R, and an estimate of motion from left to right, L–R) are represented by solid lines; predictions for inconsistent directions (e.g., physical animation from left to right, L–R, and an estimate of motion from right to left, R–L) are represented by dashed lines. (B) Similar predictions for the sinusoidal waveform.

dashed line with circle symbols). For the sinusoidal waveform the next most visible harmonic is the 11th harmonic (Table 1, row G), and the predicted velocities are lowered by a factor of 11 (relative to the first harmonic). The predictions for all velocities are represented in Figure 5b (dashed line with circle symbols).

In summary, the Fourier hypothesis predicts (a) no differences in estimates of velocity between waveforms with consistent directions, (b) lower estimates for both waveforms with inconsistent directions (relative to consistent direction conditions), and (c) lower estimates of velocity for the sinusoidal waveform than for the stair-step waveform with inconsistent directions.

The correspondence hypothesis maintains that bidirectional motion results from the presence of multiple sets of correspondences (perceived translations or movements) among the graphical elements of a display. The correspondence sets for the stair-step and sinusoidal waveforms are represented in Figure 3 (see page 436). An update of the stair-step waveform that physically translates the perceptual characteristics of the rectangles from the left to the right by the width of one element (right arrow in Figure 3a) might also be perceived as a translation from the right to the left by the width of two elements (left arrow in Figure 3a). For the sinusoidal waveform (Figure 3b), the perceived translations might be either one element to the right or 11 elements to the left. Thus the perception of bidirectional apparent motion could result from the observer's shifting attention between these alternative sets of correspondences.

The predictions for perceived velocity derived from this hypothesis can be found in Table 1 and Figure 5. No differences in velocity estimates are predicted between the stair-step and sinusoidal waveforms with consistent directions, because the critical visual features and perceptual characteristics are the same (see Table l, rows B and D, and Figure 5, solid lines with cross symbols). However, with inconsistent directions (the conditions testing for apparent motion in the opposite direction of the physical update), the correspondence hypothesis predicts a different set of perceived velocities. The effect of a two-element translation for the stair-step waveform is an increase in the predicted velocities by a factor of two (Table l, row F, and Figure 5a, dashed line with cross symbols); the effect of an 11-element translation for the sinusoidal waveform is an increase by a factor of 11 (Table l, row H, and Figure 5b, dashed line with cross symbols).

In summary, the correspondence hypothesis predicts (a) no differences in estimates of velocity between waveforms with consistent directions; (b) higher estimates for both waveforms with inconsistent directions, relative to consistent directions; and (c) higher estimates of velocity for the sinusoidal waveform than for the stair-step waveform with inconsistent directions.

The use of the AME methodology allows a direct test of whether or not bidirectional apparent motion can be seen with the two waveforms. If bidirectional motion is seen, the perceived velocities may differentiate between the Fourier and correspondence hypotheses. Both hypotheses predict the same perceived velocities for both waveforms when the physical direction and the subjective direction are consistent (solid lines in Figure 5 with the superimposed circle and cross symbols). However, the predictions diverge when the physical and subjective direction are inconsistent. The Fourier hypothesis predicts lower perceived velocities (relative to consistent directions) and a lower rate of perceived velocities for the sinusoidal wave form than for the stair-step waveform (dashed lines and circle symbols). In contrast, the correspondence hypothesis predicts higher velocities (relative to consistent directions) and a higher velocity for the sinusoidal waveform than for the stair-step waveform (dashed lines and cross symbols).

EXPERIMENT 2

Method

Participants. Five men and three women volunteered to participate. The participants' ages ranged from 26 to 59 years, and all reported having either normal or normal-corrected vision.

Apparatus. The apparatus used was identical to that in Experiment 1.

Stimuli. A single horizontal bar 19.51 cm wide and 0.38 cm high was presented on the screen, subtending a visual angle of 22.50° horizontally and 26.13 arc min vertically. Variations of the waveforms in Experiment 1 were used (see Figure 2b). The stair-step waveform consisted of three elements (47.80, 40.00, and 31.63 cd/m^2); the approximate sinusoid consisted of 12 elements (43.80, 46.79, 47.80, 46.79, 43.80, 40.00, 35.78, 32.70, 31.63, 32.70, 35.78, and 40.00 cd/m^2). The luminance contrast (C) was 20.3%, the fundamental spatial frequency was 1.43 cycles/°, and the five velocities were 2.10°, 2.79°, 3.49°, 4.19°, and 4.89°/s.

Procedure. The experiment was conducted over a three-day period with two practice sessions and one experimental session, each lasting approximately 1 h. Viewing distance was held constant using a chin rest located 50 cm from the monitor screen. Prior to each session the participants were given oral and written instructions modeled after those of Stevens (1975). Each trial consisted of the participant-paced presentation of one animated bar; the participant's task was to provide an estimate of the velocity of apparent motion. The physical direction (i.e., the physical translation of the graphical elements) could be either L–R or R–L. The subjective direction (i.e., the direction for which an observer was asked to provide an estimate) could also be in either direction. Participants reported the speed of motion for only one combination of physical and subjective direction per trial; they were instructed to report a speed of zero if no motion was apparent.

To summarize, in two practice sessions and one experimental session, a participant completed 80 trials: a factorial combination of two waveforms (sinusoidal, stair-step), five velocities (2.10°, 2.79°, 3.49°, 4.19°, and 4.89°/s), four combinations of physical and subjective directions (two consistent, L–R L–R and R–L R–L, and two inconsistent, L–R R–L and R–L L–R), and two repetitions. Presentation of trials was randomized. Following the experimental session, each participant was presented with a short questionnaire.

RESULTS

Data from only the experimental session were analyzed. A transformation was used to maintain the individual slopes and the mean of the individual intercepts of the psychophysical functions while parcelling out intra- and intersubject variability attributable to participant inconsistency (Engen, 1972). Each magnitude estimate was converted to its logarithm, and a stimulus log mean was calculated by averaging across the two repetitions. A participant mean log estimate was then calculated by averaging across all estimates for each participant; a grand mean log estimate was calculated by averaging across all estimates and all participants. Each participant mean log estimate was subtracted from the grand mean log estimate to determine an individual scaling factor. This scaling factor was added to the stimulus log mean, and the resulting values were transformed back into a linear scale. Several of the stimulus log means were zero, making this transformation impossible; these scores were reincorporated in the final data set after all nonzero stimulus log means had been reconverted into a linear scale.

A 2 × 4 × 5 repeated-measures ANOVA was performed. The assumption of noncorrelation between measures was tested using the Greenhouse-Geisser estimate of epsilon, and the probability levels were adjusted when appropriate. The main effects of waveform, $F(1, 7) = 143.94$, $p < .000006$; direction, $F(3, 21) = 4.61$, $p < .05$; and velocity, $F(4, 28) = 53.61$, $p < .000001$, were significant. The two-way interactions between waveform and direction, $F(3, 21) = 120.81$, $p < .000001$; waveform and velocity, $F(4, 28) = 11.77$, $p < .00001$; and direction and velocity, $F(12, 84) = 4.42$, $p < .00002$, were significant. The three-way interaction among waveform, direction, and velocity, $F(12, 84) = 4.63$, $p < .00001$, was also significant. The means for the three-way interaction are presented in Figure 6.

The higher-order relationship between physical and subjective directions (consistent, inconsistent) had a dramatic influence on performance, whereas direction per se did not. Four initial comparisons (using orthogonal polynomials to test for differences in linear trend associated with velocity) were conducted to test for differences associated with direction within consistent and inconsistent directions for each of the two waveforms (e.g., L–R, L–R vs. R–L, R–L for consistent directions; filled symbols in Figure 6). None of these comparisons was significant, indicating that direction per se is not critical. Therefore, this factor is not considered in the ensuing analyses. The lines in the figure represent a linear fit for each of the four combinations of waveform (stair-step, sinusoidal) and direction (consistent, inconsistent).

Two contrasts assessed differences between estimates obtained with the same waveform under consistent and inconsistent directions: a test comparing the linear trend (slopes) associated with velocity and a test comparing overall levels of performance (i.e., averaged across velocity). The results for the sinusoidal waveform (Figure 6b) indicate that both the slopes, $F(1, 7) = 40.03$, $p < .0004$, and the overall levels of performance, $F(1, 7) = 387.03$, $p < .000001$, were significantly different between the consistent and inconsistent directions. Similar contrasts for the stair-step waveform (Figure 6a) indicated that the overall levels of performance were significantly different, $F(1, 7) =$

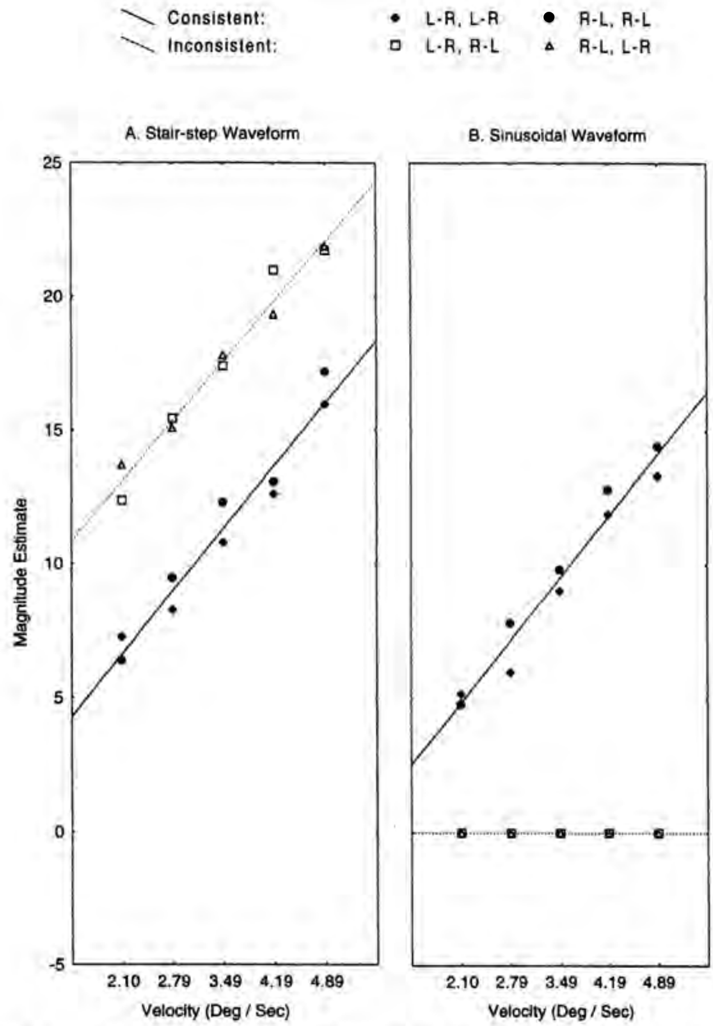


Figure 6. Magnitude estimations for apparent motion obtained in Experiment 2. (A) Mean estimates for the stair-step waveform. Filled symbols represent performance for consistent physical and subjective directions; open symbols represent performance for inconsistent directions. The solid line represents a linear function fitted to the consistent directions data; the dotted line represents a linear fit for the inconsistent directions. (B) Mean estimates for the sinusoidal waveform.

23.67, $p < .002$, whereas the slopes were not significantly different, $F(1, 7) = 0.05$, $p < .83$.

Two contrasts (linear trend, overall levels) examined differences between estimates obtained with different waveforms under similar directions. For consistent directions (Figure 6, filled symbols, solid lines), neither the overall levels of performance, $F(1, 7) = 3.30$, $p < .12$, nor the slopes, $F(1, 7) = 0.007$, $p < .94$, were significantly different between the two waveforms. The results for inconsistent directions (open symbols, dashed lines) indicate that both the slopes, $F(1, 7) = 36.73$, $p < .0006$, and the overall levels of performance, $F(1, 7) = 266.98$, $p < .000001$, were significantly different between waveforms.

DISCUSSION

The velocity estimates obtained with the stair-step and sinusoidal waveforms were very similar when observers were asked to provide estimates in the same direction as the physical update to the display (consistent directions). In fact, under these conditions the estimates of velocity were virtually identical for the two waveforms, as illustrated in Figure 6 (filled symbols, solid lines). There were, however, marked differences in velocity estimates for the two waveforms when the estimates of apparent motion were in the opposite direction of the physical update to the display (open symbols, dashed lines). The results and interpretations for the two waveforms are discussed separately.

The results for the stair-step waveform indicate that observers saw bidirectional apparent motion and that there was a reasonably good fit with the predictions derived from the correspondence hypothesis. First consider the estimates for consistent directions (Figure 6a, filled symbols, solid line). Under these conditions the observers' magnitude estimates increased in an orderly fashion as velocity increased. With inconsistent directions the magnitude estimates were higher, also increasing in an orderly fashion (Figure 6a, open symbols, dashed line).

The correspondence hypothesis predicts that if bidirectional apparent motion was present, then the velocity estimates obtained with inconsistent directions should be twice those obtained with consistent directions. For the lowest velocity the obtained differences were very close to the predictions: The average estimate was 6.82 for consistent directions and 13.03 for inconsistent directions. However, as velocity increased, the differences between consistent and inconsistent directions were underestimated relative to predictions (i.e., the slopes of the lines remain parallel, Figure 6a, instead of diverging, Figure 5a).

One potential explanation of this minor discrepancy is that observers were less sensitive to the higher velocities. Previous research has shown that sensitivity for velocity peaks between 2° and 3°/s and falls off rapidly at higher levels (Kelly, 1979); the predicted velocities for the stair-step waveform with inconsistent directions ranged from 4.19° to 9.78°/s. Thus the predictions derived from the correspondence hypothesis provide a reasonably good fit to the results that were obtained.

In contrast, these results are clearly inconsistent with the predictions derived from the Fourier hypothesis: A slower velocity of apparent motion is predicted for inconsistent directions, relative to consistent directions. This discrepancy is particularly damaging because the stimulus parameters were specifically chosen to maximize the possibility of perceiving bidirectional apparent motion with the Fourier hypothesis in mind. The second harmonic had a spatial frequency of 2.86 cycles/°, a Michelson luminance contrast of C = 10.15, and velocities ranging from approximately 1.05° to 2.44°/s; these stimulus parameters fall squarely in the range of maximal observer sensitivity for apparent motion (e.g., Bennett & Nagy, 1996; Kelly, 1979). Thus although the Fourier hypothesis provides an elegant explanation of the bidirectional apparent motion with this type of stimuli (Bennett & Nagy, 1996), and despite ample evidence that the visual system can perform Fourier-like analyses (Campbell & Robson, 1968; Kelly, 1972; Sachs et al., 1971), the present results clearly do not support this interpretation of bidirectional apparent motion.

In contrast to the results obtained with the stair-step waveform, there is no indication that observers saw bidirectional apparent motion with the sinusoidal waveform. With consistent directions the estimates obtained for this waveform were very similar to those obtained with the stair-step waveform (the solid lines in Figures 6a and 6b). With inconsistent directions, all observers on all trials entered an estimate of zero, which they were instructed to enter if they saw no apparent motion. Based on the results obtained with the stair-step waveform, one interpretation is that the 11-element translation in the direction opposite the physical update did not present a correspondence set that could be interpreted by the visual system. A second interpretation is that the velocities produced by this translation (23.05°–53.79°/s) were simply outside the range of observer sensitivity. Regardless of which interpretation is correct, these results provide a strong argument that the sinusoidal waveform should be incorporated into animated mimic displays.

GENERAL DISCUSSION

The role of waveform (luminance profile) in the design of animated mimic displays was investigated in two experiments. In Experiment 1 a variation of the method of adjustment was used, requiring observers to match velocities of apparent motion. The results indicate that the performance benefits of the sinusoidal waveform were pronounced relative to those of the stair-step waveform: Significant advantages for both accuracy and latency were found in the majority of statistical comparisons. In Experiment 2 the absolute magnitude estimation methodology was used, requiring observers to provide estimates of the velocity of apparent motion. The results also favored the sinusoidal waveform: Bidirectional apparent motion was readily perceived with the stair-step waveform but not with the sinusoidal waveform.

In summary, the results indicate that waveform is a powerful factor in the design of animated mimic displays and that the sinusoidal waveform is a viable design option. These results extend and complement the findings of a research program designed to investigate factors in the design of animated mimic displays (Bennett, 1993; Bennett & Madigan, 1994; Bennett & Nagy, 1996). The findings of this research program are summarized to provide guidance in the design of animated mimic displays that use the color-table animation technique.

Bennett (1993) investigated the role of chromatic and luminance contrast as alternative methods to define the perceptual differences between graphic elements in animated mimic displays. The results indicated that "chromatic contrast plays a secondary role relative to luminance contrast" (p. 689). Luminance contrast was very effective in producing apparent motion. For example, Bennett (1993) found that stair-step waveforms with Michelson luminance contrasts ($C = L_{max} - L_{min}/L_{max} + L_{min}$) of slightly less than 3% produced acceptable performance at the rate-matching task. However, chromatic contrast alone was not found to be effective. Thus although chromatic contrast can be used to represent categorical (e.g., that a particular pipe belongs to a particular subsystem) or qualitative (e.g., gross differences in the temperature of a fluid as it flows through a system) information, it must be used in conjunction with luminance contrast to produce effective apparent motion.

Several design issues related to luminance contrast and sinusoidal waveforms are worthy of discussion. The first is the number of graphical elements that will be required to approximate a sinusoid function. The present research indicates that 12 (Experiment 2) to 18 (Experiment 1) graphical elements (see Figure 2) will be effective for this approximation. The second issue is the amount of luminance contrast between these graphical elements. The sinusoidal waveforms evaluated in the present study had reasonably high levels of luminance contrast ($C = 27.59\%$ and $C = 20.3\%$). These levels were chosen to be representative of real-world situations in which designers would provide sufficient contrast for the animation to be seen. However, high levels of contrast may actually cause potential problems when animated mimic displays are combined with other display formats, because of the sensitivity of the human visual system to motion.

An overall goal of display design is to provide nested, hierarchical encodings in which the visual salience (prominence) of displayed information has a direct correspondence to the relative importance of that information in the domain (Bennett et al., 1997). Thus it may be desirable to lower the luminance contrast of animated mimic displays to reduce the salience of flow rate information relative to other information displayed (e.g., high-level functional and goal-related information). Therefore the integration of animated mimic displays with other display formats is a topic for future research.

Two factors that are critical in the design of animated mimic displays are spatial and temporal frequency. Although they will interact to determine perceived velocity, they are perhaps best considered independently in the present context because of practical considerations. Spatial frequencies between approximately 1.5 and 5.5 cycles/° are preferable, and 3.0 cycles/° is recommended (Bennett & Nagy, 1996). The spatial frequency of an animated mimic display will ultimately be determined by observer viewing distance, not by the physical characteristics of the display itself. Therefore, the calculations used to determine the spatial frequency of a display should incorporate an estimate of the viewing distance that is most likely to typify its use.

Temporal frequencies of 0.5 to 5.0 Hz should be used in animated displays. Bennett & Nagy (1996) summarized their recommendations:

> Considerations of temporal frequency should take first precedence and the widest acceptable range of temporal frequencies should be

> used to allow finer discriminations of flow. Thus, when there is no flow in the underlying domain there should be no apparent motion in the display. The lowest possible rate of flow in the domain should be represented by apparent motion with a temporal frequency of 0.5 Hz; the highest possible rate of flow should be represented by apparent motion with a temporal frequency of 5.0 Hz. (p. 13)

The research program has addressed a fundamental concern in the design of animated mimic displays: the factors that determine whether or not the rate of flow that is perceived by an observer maps effectively and unambiguously to the actual rate of flow that exists in the underlying domain. The addition of effective apparent motion to mimic displays could provide benefits in addition to those described in the introduction (i.e., those associated with static mimic displays). For example, the inclusion of animated mimic displays in computerized learning systems could improve the efficiency of training. Language (both spoken and written) is inherently serial in nature. However, this is not a characteristic of the majority of the complex systems that novices are required to learn about. As Hollan et al. (1984) emphasized, animated mimic displays can provide a "continuous graphical explanation" of the physical processes that constitute a complex system. This capitalizes on powerful visual pattern recognition capabilities and allows an individual to see the physical components, the connections between components, the flows of information or resources, and the associated causal relationships in real time. Thus animated mimic displays are likely to facilitate the development of appropriate conceptual understandings (mental models) of complex systems, which are critical for effective performance.

The inclusion of animation in mimic displays could also improve the detection and diagnosis of faults in real time. Normal operational states of the system would produce prototypical flow patterns in the displays; operators would develop a set of corresponding expectations about how these flow patterns should appear. Discrepancies between the expected and actual flow patterns should make faults easier to detect because of the operators' sensitivity to motion. A simple example is a situation in which there should not be any flow between two system components and yet it exists in the animated mimic display. The presence of motion would make this abnormality very detectable (in fact, a casual glance might even suffice). Animated mimic displays could also facilitate the identification of the causal factors that underlie system faults. Using the previous example, the cause of the fault could be identified directly by visually tracing the animated flow back to the point at which it became inappropriate (i.e., to the location of the stuck valve that was causing the flow).

Finally, the color table animation technique described in the present study is contrasted with several alternatives. Bennett & Madigan (1994) investigated a variation that incorporated a redundant emergent feature: graphical elements that changed the shape of their contours as a function of flow rate. For example, a lack of flow was represented by the vertical contours of the graphical elements (squares, as in the present experiment) whereas higher rates of flow were represented by an increased angling of the contours (the graphical elements changed from squares to chevron-shaped polygons). Bennett and Madigan (1994) found this technique to improve rate-matching performance. However, it requires that the physical connections between system components be redrawn each time the rate of flow changes in excess of a predetermined set point. The "engine status" animated mimic display (Figure 7a) developed by Hawkins et al. (1983b) has a similar limitation: The rate of fuel flow was represented through geometric variations (the shape of the physical connectors and movement of "bubbles" within these connectors) that need to be redrawn to produce animation. Thus, from a computational standpoint, both of these techniques are considerably less efficient than that used in the present study. Furthermore, it is likely that color table animation could be substituted for either of these techniques without sacrificing effectiveness. For example, Figure 7b illustrates how the animated portion of the engine status display might be redesigned using a sinusoidal waveform. Thus, when the physical configuration of the system being displayed will not change (as

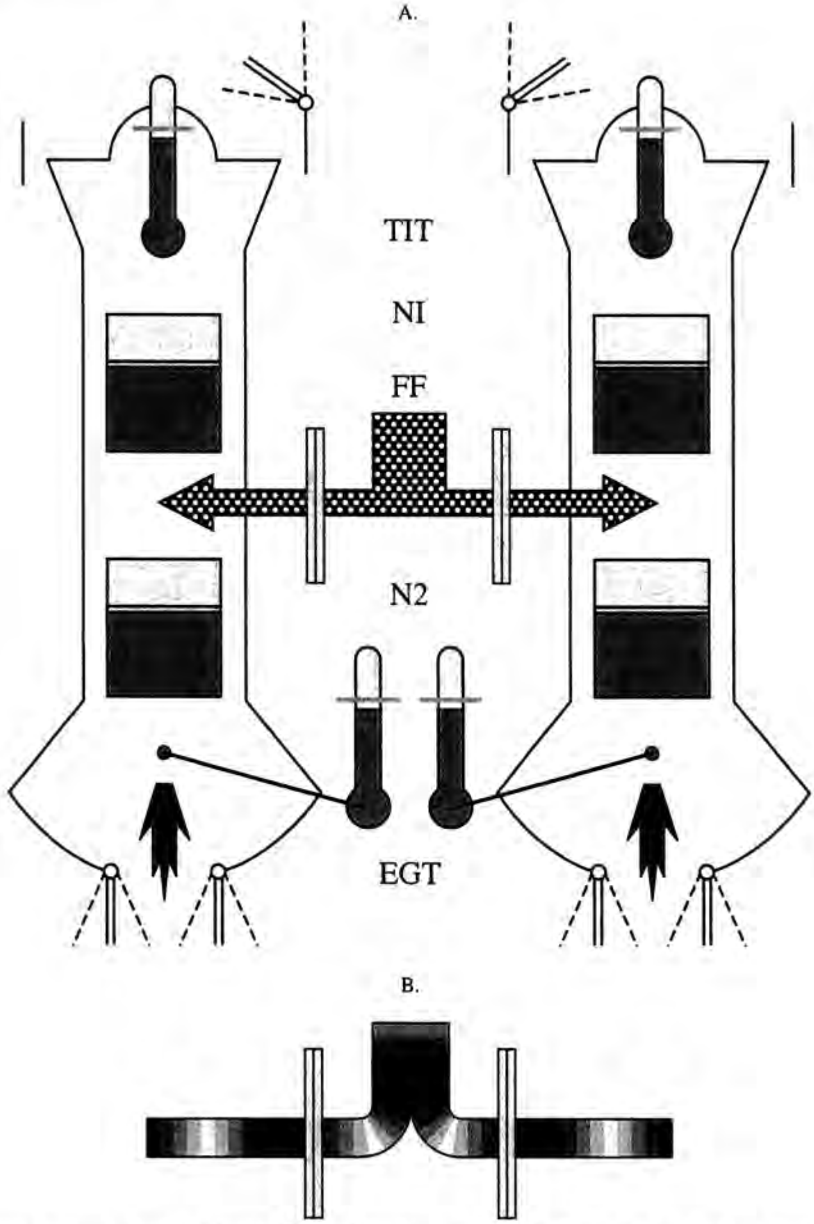


Figure 7. Animated mimic display adapted from Hawkins et al. (1983b). (A) An engine status mimic display that represents rate of fuel flow through spatial displacement of bubbles and a change in the size of the arrows (the rate of fuel flow to the two engines is equal in this example). (B) The animated portion of the display is reproduced to illustrate how it could be redesigned using an approximate sinusoid waveform. (Courtesy of the U.S. Air Force.)

will often be the case for animated functional mimic displays), color table animation is a reasonable technique for producing animation.

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