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Contours and borders in animated mimic displays

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Previous research has indicated that ambiguities in apparent motion (e.g., direction, rate) can result when color table techniques are used to produce animation in mimic displays. Two experiments were conducted to investigate alternative display designs in which contours (angled vs. straight) and borders (explicit vs. implicit) were varied. In Exp. 1 contours, borders and temporal frequency interacted. At 5 Hz angled contours improved accuracy significantly. At 10 Hz explicit borders improved accuracy significantly with angled contours, but degraded accuracy significantly with straight contours. In Exp. 2 the design of the angled contours was changed to convey less information and an additional border condition was added. Once again, borders and contours interacted: the widest explicit border degraded accuracy with straight contours. Angled contours also improved latency performance. The results suggest that angled contours can reduce ambiguity and improve the effectiveness of animated mimic displays by providing a redundant encoding of rate information. However, this benefit must be weighed against the associated computational costs. A secondary finding is that when contours are straight the borders should be implicit, not explicit. Alternative design solutions for animated mimic displays are also discussed.

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Running Title: CONTOURS, BORDERS

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INTRODUCTION

Representation aiding is a form of decision support that incorporates computerized graphical representations of a domain (Bennett, in press; Woods, 1991; Zachary, 1986). The goal of representation aiding is to provide information that supports (rather than replaces) an individual in the completion of domain tasks (Bennett, 1992). Two design goals must be achieved to ensure the success of representation aids. First, a set of appropriate conceptual perspectives, or <u>views</u> of the domain must be chosen, along with the relevant information. Second, this information must be encoded into the graphical representation so that it is easily decoded (that is, so that it matches the perceptual and cognitive capabilities of the observer). An important aspect of this encoding is the quality of the mapping between underlying system constraints and constraints in display geometry (Bennett and Flach, 1992): are changes in system constraints (e.g., system state, faults) reflected by changes in the display geometry?

One critical perspective of a domain has been referred to as the level of <u>physical function</u> (Rasmussen, 1986). This perspective provides information about the physical components of a system, and the causal connections between them. Displays that present this information have been referred to as <u>mimic</u> or <u>pictorial</u> displays. Some examples include the static (non-computerized) labels and borders that are found in many process control applications. With the advent of graphic display technology it is now possible to computerize these displays: animation techniques can be used to represent the flow of information or resources between components in an analogical fashion (e.g., Hollan, Hutchins, and Weitzman, 1984; 1987). Fig. 1 represents an exemplary animated mimic display.

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There are several potential benefits associated with animated mimic displays. These displays will be useful in computerized training systems because they provide “a ‘continuous explanation’ of the behavior of the system ... allowing a user to more directly apprehend the relationships that are typically described by experts” (Hollan, Hutchins, and Weitzman, 1987, p. 120). They will also be useful in real-time performance when <u>unanticipated variability</u> arises. In these situations the pre-planned guidance (e.g., operating procedures or automatic control sys-

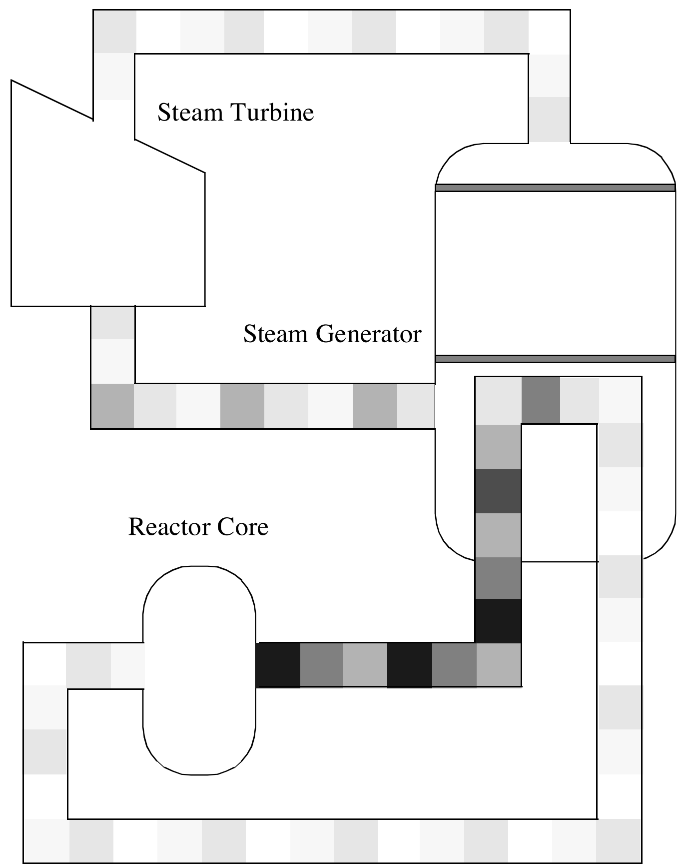

Figure 1. A representative animated mimic display.

tems) fails and the operator must consider the physical components and causal relationships in the domain to recover (what Rasmussen, 1986, has referred to as knowledge-based behavior). See Bennett (in press) for a more complete description of the potential benefits of animated mimic displays.

Despite the potential benefits very little empirical research has investigated issues in the design of animated mimic displays. In an initial study Bennett (in press) investigated a design based on the animated STEAMER displays (Hollan, Hutchins, and Weitzman, 1984; 1987). An example of this design is provided in Fig. 1: the luminance contrast profile forms a stairstep wave form (there are three repeating graphical elements that have high, medium, and low contrast). Animation (apparent motion) was provided by shifting the perceptual characteristics of the graphical elements (the squares) using color table animation techniques (Mulligan and Stone, 1989; Shoup, 1979). The nature (luminance or chromatic) and size (sub-threshold, supra-threshold) of the contrast between elements was varied while observers performed a rate-matching task (observers changed the rate of flow in a comparison display to match that of a standard display). Bennett (in press) found that the displays produced uncertainty with respect to both the rate and the direction of flow: the apparent motion could be perceived in either direction through conscious shifts in attention. The consequences of the bi-directional apparent motion was reflected in both observer strategies (slowing rate of flow in one bar to determine the appropriate direction, and then completing the rate-matching task) and the accuracy results (large errors on a small percentage of trials).

A potential explanation of this bi-directional apparent motion is based upon insights derived from Fourier analysis (Bennett and Nagy, 1992). It is possible that the visual system performs a Fourier-like analysis on the stairstep wave form, resulting in perceptible sinusoidal harmonics. The direction and rate of apparent motion for each harmonic is determined by the phase shift produced in updating the stairstep wave form. Observers may have been able to focus on these harmonics and perceive apparent motion in the opposite direction and at a much different rate than the display was intended to produce. The results of Bennett and Nagy (1992) are consistent with this explanation: better performance at low spatial and temporal fundamental frequencies was found than might be expected (the low fundamental frequencies may have produced higher sinusoidal harmonics that could be used to augment performance).

Although there may be other theoretical explanations for the bi-directional apparent motion produced by this combination of display characteristics and animation techniques, it is clear that alternativedisplay designs need to be developed. One potential solution involves the redesign of the <u>contours</u> and <u>borders</u> of the graphical elements (see Fig. 2). In Panel A the contours of the graphical elements are <u>straight</u> (they are square-shaped), and the borders between these elements are <u>implicit</u> (defined by the perceptual characteristics of adjacent elements). This is the display configuration used in the STEAMER animated mimic displays (Hollan, Hutchins, and Weitzman, 1984; 1987) and in previous research (Bennett, in press; Bennett and Nagy, 1992). One modification to this design is represented in Panels C and D. In this display configuration the contours change shape (become more or less <u>angled</u>) in response to a change in the rate of flow. A medium rate of flow from left to right is illustrated; no flow would be represented by a straight contour. A second modification is illustrated in Panels B and D: the borders are <u>explicit</u> (defined explicitly by dark, thin lines between the graphical elements).

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Insert Figure 2 about here

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Supplementing apparent motion with angled contours may improve the effectiveness of animated displays for several reasons. First, the orientation of the angled contours should reduce uncertainty about the direction of flow. Second, the size of the angles produced by the contours will provide a redundant cue (in addition to apparent motion) to assist in determining the rate of flow. This type of perceptual information has been referred to as <u>emergent features</u>: “the high-level, global perceptual features that are produced by the interactions between individual parts, or graphical elements, of a display...” (Bennett, Toms, and Woods, 1993, p. 73). The role of borders is less-well defined. The explicit border condition could emphasize the redundant source of information that is provided by contours. However, it is also possible that these static delimiters may actually degrade the quality of apparent motion.

The first experiment investigated the effects of borders and contours on performance of a rate-matching task, and was designed to replicate and extend previous findings. The four contour/border display configurations represented in Fig. 2 were the primary experimental manipulation. With the exception of minor methodological variations (e.g., the luminance and chromatic con-

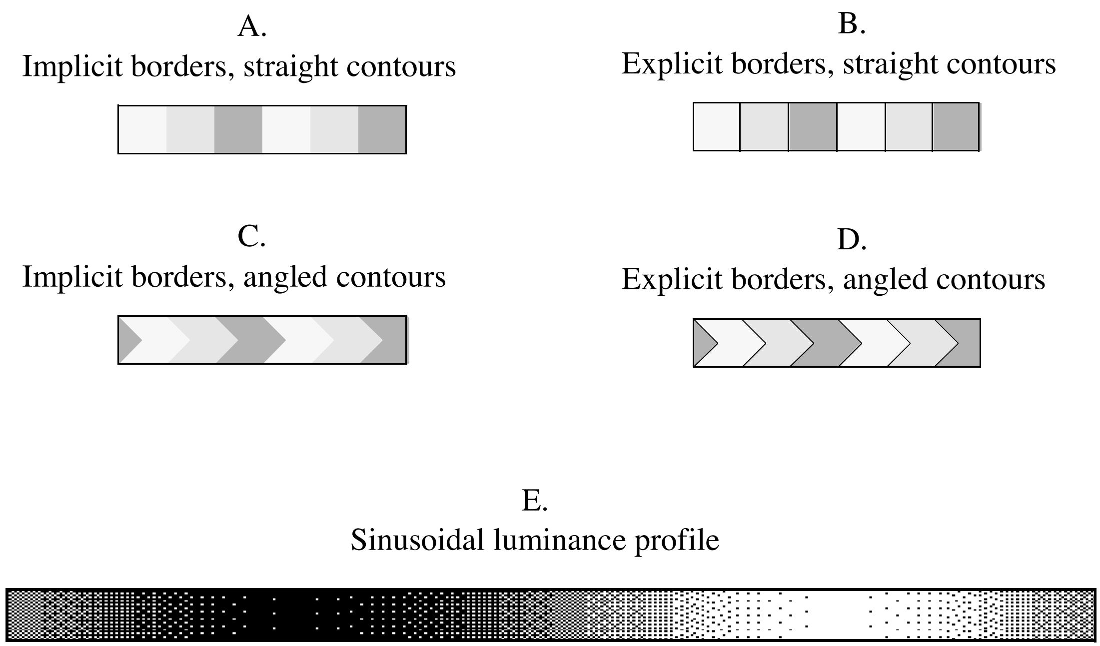

Figure 2. Fig. 2a. Implicit borders, straight contours. Fig. 2b. Explicit borders, straight contours. Fig. 2c. Implicit borders, angled contours. Fig. 2d. Explicit borders, angled contours. Fig. 2e. Sinusoidal luminance profile.

trast of the graphical elements) and the addition of three display configurations (those represented in Fig. 2, Panels B, C, and D) the study replicates Experiment 2 of Bennett (in press). The critical stimulus parameters are summarized in Table 1.

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Insert Table 1 about here

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EXPERIMENT 1

Method

Subjects. Seven observers (4 males and 3 females) participated in the experiment and were paid $5.00 an hour. Their ages ranged from 20 to 25 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 GDM-1604-15) with a resolution of 1152 by 900 pixels was used to present the stimuli and experimental prompts. The monitor had a refresh rate of 66 Hz, non-interlacing.

Stimuli. Two horizontal bars were presented on a medium grey background (u’ = 0.2004, v' = .4668, cd/m^2 = 3.86). Each bar contained 20 graphical elements; three levels of luminance contrast cycled every third graphical element (see Fig. 2). The lower bar was the standard bar. Apparent motion was produced by shifting the perceptual characteristics of the graphical elements from the right to the left at a raw update rate of either 15 or 30 Hz. Because there were three elements in a cycle, the temporal frequency of the standard bar was either 5 or 10 Hz (Hz will be used to refer to rates of temporal frequency expressed in terms of the wave form, rather than the screen refresh rate, unless otherwise noted). 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 3.33, 6.67, 8.33 or 11.67 Hz, and the perceptual characteristics of the graphical elements could be shifted in either direction.

The contour of the graphical elements was varied across trials (see Fig. 2) and could assume one of two shapes: angled or straight. In the straight contour condition (Panels A and B in Fig. 2) the shape of the graphical elements remained the same (square). In the angled contour condition (Panels C and D in Fig. 2) the shape of the graphical elements became more or less arrow-shaped as temporal frequency changed (a medium flow from left-to-right is depicted). Discrete thresholds (preset at equal intervals of 0.55 Hz) were used to determine when a change in display geometry occurred: each time a threshold was passed the edges of the graphical elements were displaced one pixel. Thus, when the temporal frequency of the bar was between 0.00 and 0.55 Hz the edges of the graphical elements were displaced 0 pixels; when the temporal frequency was between 0.56 Hz and 1.10 Hz the edges were displaced 1 pixel, etc. The size of the angles that were produced ranged from 180 deg at 0 Hz, to 21.24 deg at 22 Hz (smaller angles could also be produced if the observer demanded greater temporal frequencies).

The border between graphical elements was also varied across trials. In the implicit border condition (Panels A and C in Fig. 2) the boundary between graphical elements was defined by the perceptual characteristics of adjacent graphical elements (primarily luminance contrast). In the explicit border condition (Panels B and D in Fig. 2) the boundary between graphical elements was defined by a black vertical line with a width of one pixel (this line subtended approximately 104.8 arc sec, assuming an observer seating distance of 50 cm). As Fig. 2 implies, borders and contours were combined factorially for a total of four display configurations.

Each bar was 7.6 cm wide and 0.38 cm high (all reported measurements are for straight contours). 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 approximately 50 cm, which will be assumed in all calculations. Each bar subtended a visual angle of 8.64 deg horizontally and 26.13 arc min vertically; the distance between the bars subtended a visual angle of 5.48 deg. Each graphical element was 0.38 cm high and 0.38 cm wide. Thus, each graphical element subtended a visual angle of 26.13 arc min both horizontally and vertically. The width of the explicit border subtended a visual angle of 10.48 arc sec. A cycle (three graphical elements) subtended a visual angle of 1.31 deg, and had a fundamental spatial frequency of 0.77 c/deg.

Four levels of luminance contrast were used. Contrast was measured with a Minolta Chroma Meter (model CS101), and the average luminance contrasts for the four experimental conditions were 1.00%, 3.47%, 6.76%, and 9.96%. These values were calculated using the Michelson formula, C = (Lmax - Lmin)/2 $(\overline{L})$: Lmax is the largest of the measured luminance values for the three repeating graphical elements, Lmin is the smallest, and $\overline{L}$ is their mean. The chromatic contrast was approximately equal, with average values of u’ = 0.1830 and v’ = 0.5461 (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 a verbal 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 temporal frequency of the comparison bar to match the temporal frequency of the standard bar. The initial temporal frequency of the comparison bar (3.33, 6.67, 8.33 or 11.67 Hz) was either higher or lower than that of the standard bar (5 or 10 Hz). The four 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. Subsequent increments depended upon 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 this 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. Measures of accuracy and latency (accurate to 1/100 of a second) were obtained for each experimental trial. Observers were provided with feedback for accuracy, but not for latency.

To summarize, in each of 5 experimental sessions (Days 1 through 5) an observer completed 64 trials: a factorial combination of contour (straight or angled), border (explicit or implicit), luminance contrast (C = 1.00%, 3.47%, 6.76%, or 9.96%), direction of apparent motion (right or left), and temporal frequency of the standard bar (5 or 10 Hz).

RESULTS

Accuracy. All raw scores in which the temporal frequency of the comparison bar was greater than 22 Hz were dropped from the analyses (once the temporal frequency exceeded the refresh rate of the monitor the direction of apparent motion was indeterminate). Of the 2240 data points, 24 (1.07%) were removed using this criterion. For the remaining scores error magnitude was obtained by taking the absolute value of the difference between the temporal frequency (Hz) of the comparison and standard bars. The remaining scores were averaged across direction for a total of 32 scores per observer.

A 5 (day) x 2 (contour) x 2 (border) x 4 (luminance contrast) x 2 (temporal frequency) repeated-measures ANOVA was performed on these scores. The assumption of non-correlation between repeated measures was checked by calculating the Greenhouse-Geiser estimate of epsilon. For effects where this assumption was violated the appropriate reduction in degrees of freedom were made (when appropriate these adjustments were made for all statistical comparisons in both experiments). The main effects of contour, $F(1,6) = 11.35$, $p < 0.02$, temporal frequency, $F(1,6) = 30.38$, $p < 0.002$, and luminance, $F(3,18) = 22.79$, $p < 0.0001$ were significant. The interaction effects between contour and border, $F(1,6) = 66.18$, $p < 0.0002$, contour and temporal frequency, $F(1,6) = 8.09$, $p < 0.03$, contour, border, and temporal frequency, $F(1,6) = 29.30$, $p < 0.002$, and luminance and temporal frequency, $F(3,18) = 6.43$, $p < 0.02$, were significant. All other effects were not significant. Only selected aspects of these results will be discussed.

The main effect of temporal frequency indicated that performance was significantly better for 5 Hz than for 10 Hz. The main effect of contour indicated that performance was significantly better for angled contours than for straight contours. The interaction effect between contour and temporal frequency indicated that performance benefits for angled contours were more pronounced at 10 Hz than at 5 Hz.

The interaction effect between contour and border indicated that performance benefits due to angled contours were more pronounced for the explicit border condition than for the implicit border condition (see Fig. 3a). The significant three-way interaction effect between contour, border and temporal frequency indicated that this relationship was found only at 10 Hz (see Fig. 3b): there was no effect of contour when border was implicit, but a large effect when border was explicit (accuracy was improved significantly with angled contours and degraded significantly with straight contours). In contrast, there was no significant interaction between contour and border at 5 Hz. Instead, there was a simple main effect indicating that angled contours improved performance significantly, relative to straight contours.

Latency. A similar repeated-measures ANOVA was performed on the latency scores. The main effects of temporal frequency, $F(1,6) = 9.90$, $p < .02$, and experimental session, $F(4,24) = 17.78$, $p < .002$, were significant. All other effects were not significant. Observers spent significantly more time to complete the task for 5 Hz than for 10 Hz. Latency improved significantly during the first three experimental sessions but did not improve significantly during the last two experimental sessions.

DISCUSSION

The results indicate that incorporating borders and contours in animated mimic displays can reduce uncertainty and improve an observer's capability to extract rate-of-flow information. In general, the presence of angled contours improved performance significantly (see Fig. 3). Angled contours provide a highly salient emergent feature (the orientation and size of the angle) that testifies about the direction and rate of flow in the underlying domain. This visual information can be used in addition to, or in place of, the apparent motion produced by the display. The effect of borders depended upon the type of contour in the display configuration. In general, the presence of explicit borders facilitated performance when the contours were angled, but degraded performance when the contours were straight. The improvements in performance for explicit borders may have resulted because the borders accentuate the redundant information provided by angled contours. The decrements in performance may have resulted because the explicit borders disrupt the quality of the apparent motion that is produced by the displays when the contours are straight.

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Insert Figure 3 about here

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A general conclusion that can be drawn from these results is that if a mimic display has angled contours then the borders should be explicit, and conversely, if the contours are straight then the borders should be implicit. Inspection of the 24 scores that were not considered in the ANOVA reinforce this conclusion. Fewer scores were dropped from the straight/implicit (4) and

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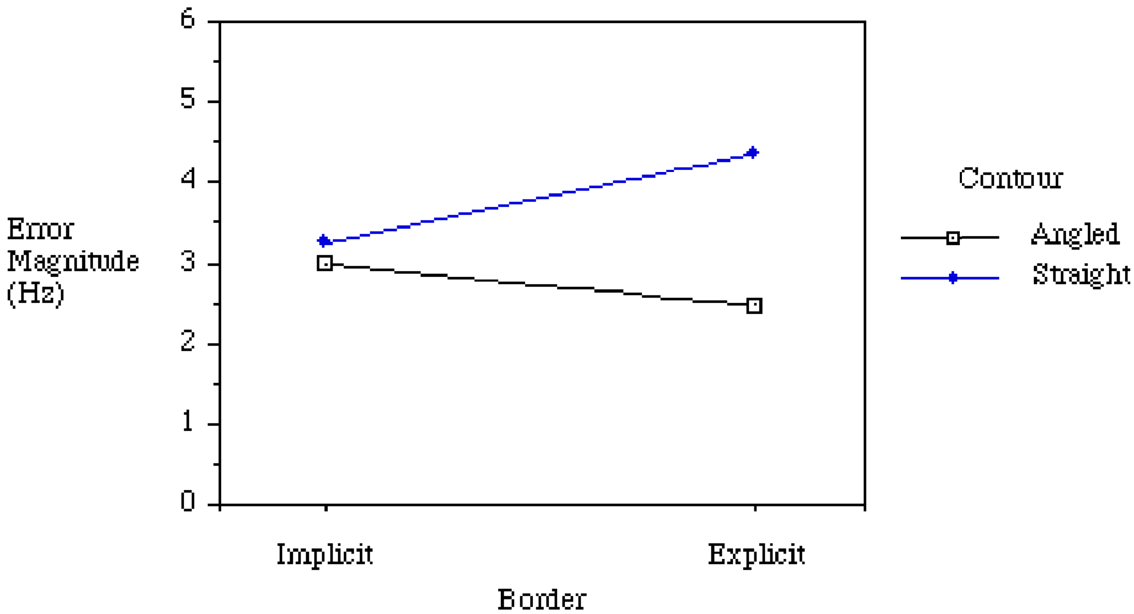

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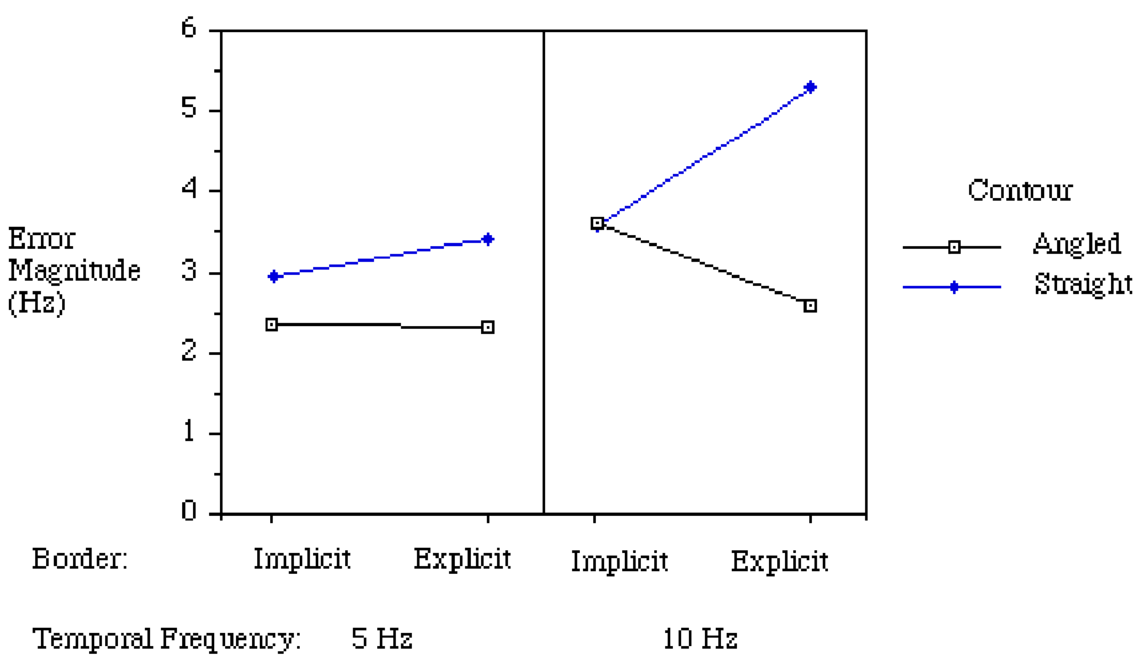

Figure 3. Fig. 3a. Mean error magnitude (Hz) for the interaction effect between borders and contours in Experiment 1. Fig. 3b. Mean error magnitude (Hz) for the interaction effect between borders, contours, and temporal frequency in Experiment 1.

the angled/explicit (3) conditions than from the straight/explicit (11) and the angled/implicit (6) conditions. Although this distribution of scores only approached significance ($x^2 = 3.703$, $p < 0.0543$), the findings complement those described in the previous paragraph.

Experiment 2 was designed to replicate and extend these findings. A primary manipulation involved the design of the angled contours. In the first experiment the edges of the angled contours could become quite extended: at the maximum update rate of the monitor the outer-most edge of each contour was offset approximately 2 1/2 graphical elements. For comparison purposes the edge of the angled contours in Fig. 2, Panels C and D, have an offset of approximately 1/2 graphical element. There are both advantages and disadvantages to this display configuration. One advantage is that a change in the display geometry conveys a great deal of information about the corresponding physical change in the rate of flow. One disadvantage is that this resolution incurs a computational cost: the graphical elements and contours must be redrawn at frequent intervals. In addition, at higher rates moire-like optical illusions can be produced by the angled contours. In Experiment 2 the angled contours were redesigned so that the outer-most edges did not extend past the farthest border of an adjacent graphical element. This reduces the computational requirements and the possibility of optical illusions, but also reduces the information conveyed by changes in display geometry.

A second major methodological change involved borders. The range of border widths was extended to examine the associated performance decrements more closely. The two border conditions in Experiment 1 (implicit -- defined by the perceptual characteristics of adjacent graphical elements, and explicit -- defined by a dark line one pixel wide) were retained. In addition, a third border condition with an explicit border three pixels wide was added in Experiment 2 (the terms <u>explicit-3</u> and <u>explicit-1</u> will be used to differentiate between these two conditions). In contrast to Experiment 1 the viewing distance was doubled (approximately) and held constant through the use of a chin-rest. Thus, the visual angle subtended by the width of the explicit-1 border condition is less than that in Experiment 1, while the visual angle subtended by the explicit-3 condition is greater. There were also some minor methodological changes in Experiment 2, and the changes in critical stimulus parameters are summarized in Table 1.

EXPERIMENT 2

Method

Subjects. Five female and three male observers participated in the experiment and were paid $5.00 per hour. All observers had normal or normal-corrected vision. All eight observers had participated in previous experiments using similar procedures but different stimuli. One subject was dropped from the analysis due to a failure to complete the task effectively.

Apparatus. The same apparatus was used in the previous experiment, except for the addition of a head/chin rest (Lafayette Instruments, model 14300).

Stimuli. All aspects of the stimuli were the same as Experiment 1, with the following exceptions. Two major changes involved the border and contour conditions. In addition to the two border conditions in Experiment 1 (implicit, explicit-1), a third border condition was added in Experiment 2. The new condition had an explicit border that was three pixels wide (explicit-3). The second major change involved the angled contours. The discrete thresholds that determined changes in display geometry (a one-pixel displacement of the angled contour) was increased from 0.55 Hz in Experiment 1 to 1.375 Hz in Experiment 2. Because the maximum temporal frequency was limited to 22 Hz, the maximum offset of the contours did not exceed 0.4064 cm (one graphical element). Thus, the angles produced in the angled contour conditions ranged from 180 deg (0 Hz) to 50.23 deg (22 Hz).

Five sets of stimuli were developed with luminance contrasts of C = 11.69%, 7.75%, 5.44%, 4.40%, and 3.85%. The chromatic contrast of these stimuli was approximately equal. The physical displacement of the graphical elements in both bars was always from the left to the right. The temporal frequency of the standard bar was 7.33 Hz throughout all trials. There were six initial rates for the comparison bar (1.00, 2.00, 3.00, 11.00, 12.00 or 13.00 Hz).

The viewing distance was fixed at 100 cm. Each bar contained forty graphical elements. The height of each graphical element was 0.38 cm, and therefore each bar subtended (vertically) a visual angle of 13.10 arc min. The width of each graphical element varied, depending upon the border condition. In the implicit border condition the width of each graphical element was 0.4064 cm and therefore the width of each graphical element subtended a visual angle of 13.97 arc min.

In this condition, one cycle of the three repeating graphical elements subtended a vertical visual angle of 41.91arc min and had a fundamental spatial frequency of 1.43 c/deg.

For the two explicit border conditions the baseline width of each graphical element remained the same, but the effective width of each graphical element was increased to accommodate the border. For the explicit-1 condition the width of the graphical element plus border was increased to 0.4318 and the corresponding visual angle was increased to 14.84 arc min. The visual angle subtended by the explicit-1 border alone was 52.39 arc sec. For the explicit-3 border condition the width of the graphical element plus border was increased to 0.4826 cm, increasing the visual angle to 16.59 arc min; the width of the explicit-3 border was 157.17 arc sec. Similarly, the overall width of the bars varied, ranging from 16.26 cm (implicit border), 17.27 cm (explicit-1), to 19.30 cm (explicit-3). The horizontal visual angles subtended by these bars were 9.23 deg, 9.80 deg, and 10.92 deg, respectively.

Procedure. The procedure was the same as the previous experiment, with the following exceptions. The experiment was conducted during a five-day period with one experimental session per day. The amount of luminance contrast remained the same during an experimental session, but was reduced between sessions. A chin-rest was used to maintain the viewing distance at 100 cm. The maximum temporal frequency of the comparison bar was limited to 22 Hz (corresponding to the maximum refresh rate of the monitor). 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.

To summarize, the three types of borders (implicit, explicit-1, and explicit-3) and the two types of contours (straight and angled) were combined factorially to produce six display configurations. There were six initial temporal frequencies for the comparison bar and two repetitions, for a total of 72 trials during each of five experimental sessions (Days 1 through 5, with decreasing luminance contrasts of C = 11.69%, 7.75%, 5.44%, 4.40%, and 3.85%).

RESULTS

Accuracy. The accuracy scores were averaged across repetition and the initial temporal frequency of the comparison bar for a total of 6 scores per observer, per experimental session. A 5 (luminance contrast) x 3 (border) x 2 (contour) repeated-measures ANOVA was performed on these data. The main effects of border, $F\ (2,12) = 7.56$, $p < 0.02$, and contour, $F\ (1,6) = 9.35$, $p <$

0.03, and the border by contour interaction, F (2,12) = 6.37, $p < 0.04$, were significant. All other effects were not significant.

The main effect of contour indicated that performance was significantly more accurate with angled contours than with straight contours. The main effect of border indicated that performance was significantly less accurate in the explicit-3 condition than in the explicit-1 or the implicit condition. The significant border by contour interaction effect indicates that performance with the straight contour and the explicit-3 border was significantly worse than performance with the other contour/border combinations (see Fig. 4).

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Insert Figure 4 about here

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Latency. The same repeated-measures ANOVA was performed on the averaged latency scores. The interaction between contour and day (luminance contrast) was significant, F (4,24) = 5.85, $p < 0.02$. All other effects were not significant. The means for this effect are illustrated in Fig. 5a. With angled contours observers decreased latency significantly with additional experience at the task, despite the fact that the luminance contrast of the graphical elements was also decreasing. There were significant advantages for angled contours, relative to straight contours, on the final two days.

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Insert Figure 5 about here

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DISCUSSION

The results of Experiment 2 provided additional evidence that angled contours can be effective in decreasing ambiguity and increasing the capability of observers to extract rate-of-flow information from animated mimic displays. Performance with angled contours was more accurate than performance with straight contours in all three border conditions, and significantly more accurate for the explicit-3 border condition (see Fig. 4). A significant performance advantage was also found for latency. As observers gained experience at the task they responded more quickly with the angled contours (see Fig. 5a). This is despite the fact that the luminance contrast was reduced systematically between experimental sessions. As Figure 5b illustrates, with straight

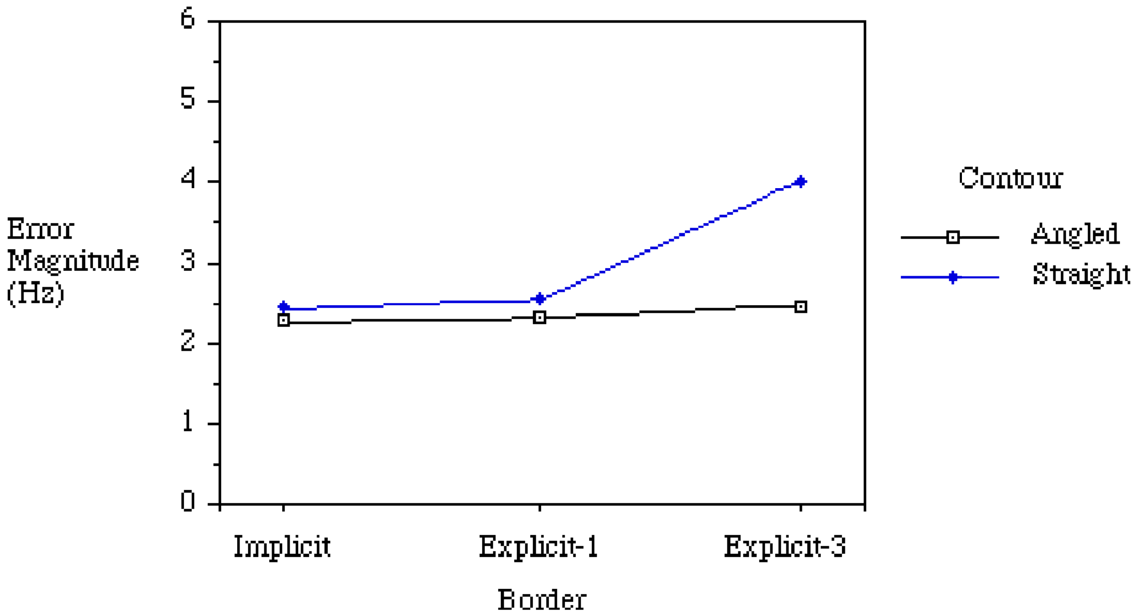

Figure 4. Mean error magnitude (Hz) for the interaction effect between borders and contours in Experiment 2.

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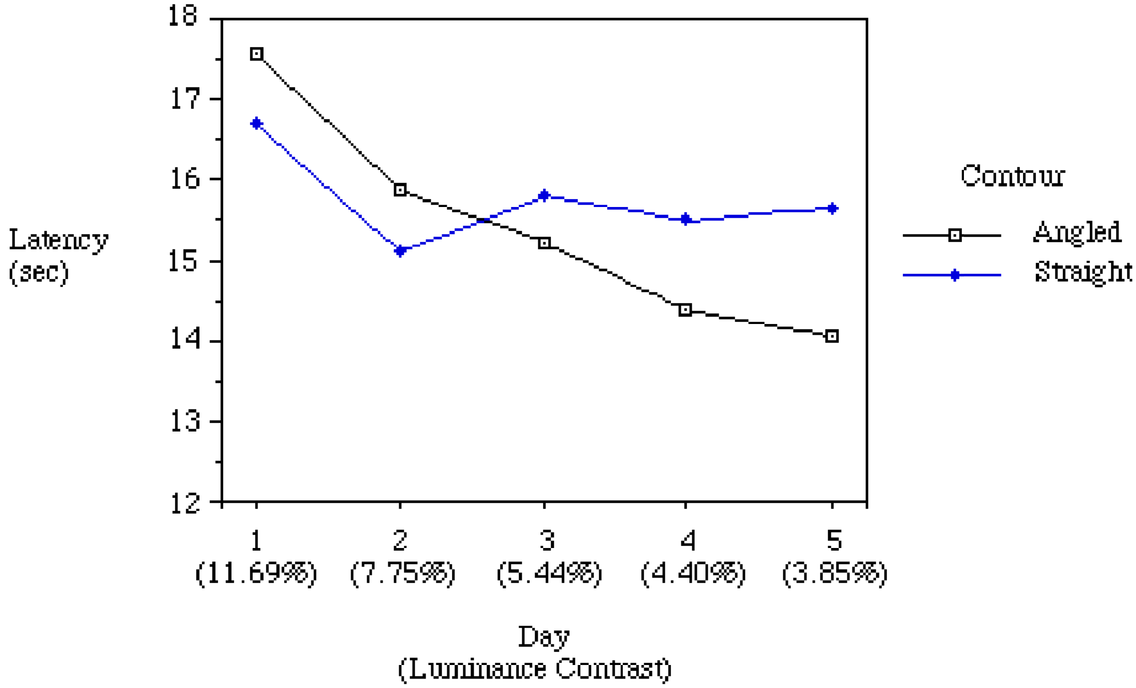

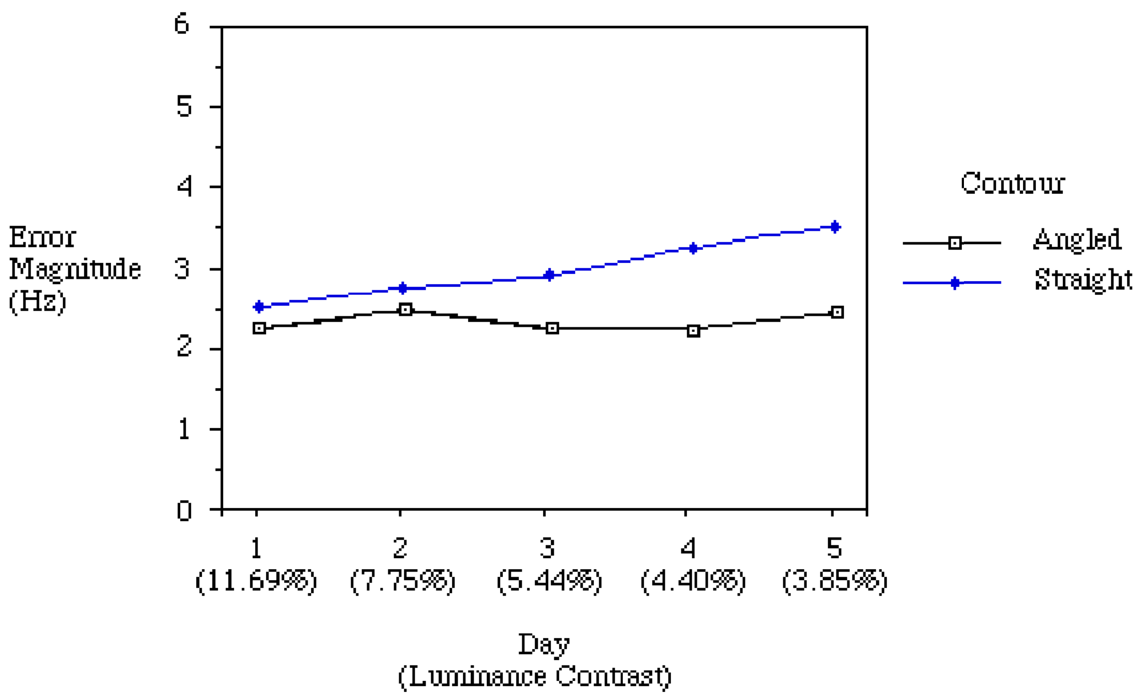

Figure 5. Fig. 5a. Mean latency (seconds) for the interaction effect between borders and contours in Experiment 2. Fig. 5b. Mean error magnitude (Hz) for the interaction effect between borders and contours in Experiment 2.

contours the reduction in contrast was accompanied by a decrease in accuracy (this interaction was not significant, it is provided for illustrative purposes only).

It should be remembered that these results were obtained with redesigned contours that reduced the amount of information conveyed by a change in the display geometry (see Table 1). In Experiment 1 the contours were displaced approximately 2 1/2 graphical elements, relative to straight contours, at the maximum update rate of the screen (as a frame of reference, the vertices in Fig. 2 extend approximately 1/2 of a graphical element). The smallest change in display geometry, a one-pixel displacement, represented a change in temporal frequency of 0.55 Hz. In Experiment 2 the vertices were displaced a maximum of one graphical element, and a one-pixel displacement represented a 1.375 Hz change in temporal frequency. In addition, the viewing distance was doubled (approximately) in Experiment 2, which made a one-pixel displacement more difficult to detect. Despite the decrease in the amount of information conveyed by angled contours this display configuration still clearly facilitated performance.

The results of Experiment 2 also clarified the role of borders in animated mimic displays. In Experiment 1 it was found that explicit borders facilitated accuracy when the contours were angled and temporal frequency was high (10.00 Hz). In Experiment 2 an intermediate temporal frequency was employed (7.33 Hz) and there was no evidence that explicit borders improved performance for angled contours (see Fig. 4). Thus, it can be concluded that the performance benefits for explicitely representing angled contours is weak at best. A more robust finding of Experiment 1 was that explicit borders degraded accuracy when the contours were straight. In Experiment 2 a performance decrement was found for explicit borders and straight contours, but only for one of two explicit border conditions: accuracy was degraded significantly for the explicit-3 border condition, but not for the explicit-1 border condition.

These findings suggest that explicit borders have the potential to disrupt the accurate perception of apparent motion, and that this potential may be realized when the width of the explicit borders exceed a critical size. The two explicit border conditions in Experiment 2 subtended a larger (explicit-3, 157.17 arc sec) and a smaller (explicit-1, 52.39 arc sec) visual angle than the explicit border condition in Experiment 1 (approximately 104.78 arc sec). Thus, it appears that the subjective impression of apparent motion is not disrupted by the presence of explicit borders that subtend small visual angles. This finding is not surprising, given that long-range processes are involved (Braddick, 1974) which invoke both central and peripheral mechanisims (see Kolers, 1963, for a striking example of the potential effects of central mechanisims in apparent motion). However, as the explicit border becomes wider the subjective impression of apparent motion is disrupted: the graphical elements appear to be blinking rather than moving. The exact point at which this transition occurs cannot be determined from these experiments, but lies between 5.24 and 15.78 arc sec -- the width in the two controlled viewing distances in Experiment 2.

One potential explanation of the disruption of apparent motion is ecologically-based. Borders that subtend a large visual angle may be interpreted as a frame of reference by the visual system. A frame of reference is a critical source of spatial information in real world scenes. For example, objects that are in motion will either occlude other objects in the visual frame of reference, or will be occluded by them. Which of these two perceptual events occurs depends upon the spatial relationships between 1) the observer, 2) the object in motion, and 3) the other objects in the frame of reference. This information is a critical factor in determining the three-dimensional characteristics of the world from the two-dimensional projection on the retina (Gibson, 1966). In animated mimic displays the combination of straight contours and explicit borders may have provided a visual frame of reference and an associated set of expectations. Based on real-world experience with actual objects in motion, the graphical elements should either occlude (pass in front of), or be occluded by (pass in back of) the explicit borders. Since neither of these two perceptual events occur the visual system may be less likely to attribute motion to the graphical elements.

GENERAL DISCUSSION

Mimic displays provide critical information about an underlying domain (e.g., Rasmussen, 1986) and the animation of these displays has the potential to improve both the effectiveness of real-time performance (Bennett, in press) and the efficiency of training (Hollan, Hutchins, and Weitzman, 1984; 1987). Although color table animation is an effective method to provide animation, there are potential problems with these displays. Previous results suggest that ambiguity with respect to both direction and rate of flow may arise when prominent examples (e.g., Hollan, Hutchins, and Weitzman, 1984; 1987) are used as a model for implementation (Bennett, in press; Bennett and Nagy, 1992). The alternative display designs investigated in the present study have the potential to improve the effectiveness of animated functional mimic displays.

Contours.

In general, it can be concluded that angled contours improve the capability of observers to extract rate-of-flow information from animated mimic displays. In both experiments observers performed the task more accurately with angled contours than with straight contours in most experimental conditions. In addition, the benefits in accuracy were not obtained at a cost in latency. In fact, with additional experience in Experiment 2 observers decreased (significantly) the amount of time required to perform the task when the contours were angled. The most likely explanation of these results is a very simple one: the angled contours provide a redundant encoding of rate information that can be used to supplement the apparent motion that is produced by the displays. The orientation and size of the angles produced by the contours are highly salient perceptual features that testify about the underlying system state.

It should be noted, however, that there are computational costs associated with angled contours. With straight contours the physical connections between system components are drawn only once and animation is provided by changing the color table entries (the RGB values) and resetting the color table. With angled contours the entire physical connection must be redrawn each time that the change in flow exceeds a threshold value. These computational costs could be prohibitive. Factors that will determine the extent of these costs include the volatility of the flow rate associated with the information or resource being represented, the sheer number of graphical elements, and the size of the preset, discrete threshold that is chosen.

Given that angled contours will be an appropriate design option for selected applications, it is useful to consider additional issues in their design. A critical issue in display design is the quality of the mapping between the emergent features produced by a display and the underlying domain (Bennett and Flach, 1992; Bennett, Toms, and Woods, 1993). In the present displays the display geometry changed (becoming more or less angled by a one-pixel displacement) when the rate of flow crossed a fixed threshold. Because the thresholds were spaced at equal intervals, the change in angle size (i.e., the change in the emergent feature) varied with the rate of flow. For example, in Experiment 2 surpassing the first threshold (1.375 Hz) caused the angles to change by approximately 15 degrees, while surpassing the last threshold (20.625 Hz) caused the angles to change by approximately 3 degrees.

This is a reasonable first approximation for design. Research on the psychophysics of angle judgements indicates that observers tend to over-estimate acute angles and undere-stimate obtuse angles (Fisher, 1969; Maclean and Stacey, 1971; MacRae and Loh, 1981). Thus, the design of present displays (which provided a larger change in angle size with larger angles, and vice-versa) is consistent with these findings. It is likely, however, that changes in display geometries that more closely approximate the psychophysical crossover functions could be obtained by changing the spacing of threshold intervals. In addition, the previously-mentioned studies indicate that observer tendencies to over- or under-estimate angles change as a function of orientation. Thus, different changes in display geometry may be required for horizontal and vertical orientations.

Borders.

The role of borders in the design of animated mimic displays is less clear-cut. The results of Experiment 1 indicate that the use of explicit borders may have the potential to improve performance when the contours are angled. At higher temporal frequencies explicit borders improved performance significantly, presumably by increasing the salience of the emergent features provided by the contours. However, significant performance advantages were not evident at lower temporal frequencies in Experiment 1, nor were any performance advantages evident in Experiment 2. At best it can be concluded that explicit borders do not harm performance when the contours are angled. In contrast, the results of both Experiments 1 and 2 indicate that the presence of explicit borders and straight contours can degrade the quality of apparent motion that is produced by animated mimic displays. In summary, although explicit borders may be included in animated mimic displays when the contours are angled, they should not be included when the contours are straight.

Conclusions

The present experiments have investigated display configurations that preserve the design characteristics of the most prominent examples of animated mimic displays. In these displays the luminance contrast assumes a stairstep profile. An alternative design strategy is to employ graphical elements where the luminance contrast approximates a sinusoidal profile, rather than a stairstep profile. An example is provided in Fig. 2e. Using sinusoidal luminance profiles could minimize or eliminate harmonics that may be responsible for the ambiguities in flow (Bennett and Nagy, 1992). Preliminary research indicates that these alternative display designs improve observers' ability to extract rate-of-flow information: significant advantages in both accuracy and latency were obtained. An additional benefit is that the computational efficiency of color-table animation is retained.

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Table 1. Critical stimulus parameters for Experiments 1 and 2.

	Experiment 1.	Experiment 2.
Fundamental spatial frequency	0.77 cyc/deg	1.43 cyc/deg
Temporal frequency of standard bar	5.00, 10.00 Hz	7.33 Hz
Initial temporal frequency of comparison bar	3.33, 6.67, 8.33, 11.67 Hz	1.00, 2.00, 3.00, 11.00, 12.00, 13.00 Hz
Luminance contrast	1.00, 3.47, 6.76, 9.96 cd/m^2	3.85, 4.40, 5.44, 7.75, 11.69 cd/m^2
Contours	angled, straight	angled, straight
Discrete threshold	0.55 Hz	1.375 Hz
Size of angles	180 deg at 0.00 Hz; 21.24 deg at 22.00 Hz	180 deg at 0.00 Hz; 50.23 deg at 22.00 Hz
Viewing distance	≈ 50 cm	100 cm
Borders	implicit, explicit-1	implicit, explicit-1, explicit-3
Visual angle subtendedby explicit border	≈ 104.78 arc sec	52.39 arc sec; 157.17 arc sec

LIST OF FIGURES