To appear in the *Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society*. Santa Monica, Human Factors and Ergonomics Society, 2003.

USING MOTION TO VISUALIZE FLOW FACILITATES MONITORING IN PROCESS CONTROL

Gavin R. Essenberg[1], Douglas A. Wiegmann[1], Thomas J. Overbye[2], and Yan Sun[2]
[1]Aviation Human Factors Division, Institute of Aviation
University of Illinois at Urbana-Champaign
Savoy, Illinois
[2]Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois

In this experiment, we examined the use of motion in displays to illustrate power transactions in a large-scale electrical power network. Participants located and selected the selling and buying nodes for a single power transaction in each trial based on patterns in power flow between the nodes in the network, and they designated an arbitrary power flow path from the seller to the buyer in trials where they were not directly connected. Participants performed the tasks using interactive displays indicating power flow with stationary arrows, arrows moving at a uniform speed, and arrows moving at a speed proportional to power flow. The two motion displays supported faster selection times, fewer errors, and lower workload than the no-motion display. Selection times and error rates were slightly lower in the proportional-motion display than in the uniform-motion display, but the differences were not significant. These results indicate that motion used in displays to indicate flow among system components can significantly improve performance in tasks that require detection of specific flow patterns.

INTRODUCTION

The interconnected electric power grid in North America is among the largest and most complex systems ever built, consisting of billions of individual components, tens of millions of miles of wires and thousands of individual generators (Overbye, 2000). Power system operators need to interpret and integrate multiple measured parameters from each component in the areas of the power grid for which they are responsible (Overbye, Klump, & Weber, 1999). They then use that information to perform tasks typical of process control, requiring consistent monitoring of the power grid and detection of faults, such as insufficient or excessive component voltages, due to transmission line overloads and outages (Wiegmann, Rich, Overbye, & Zhang, 2001).

Some power system operators must also monitor and analyze power transfer distribution factors (PTDFs), which show the percentages of an individual power transaction from one selling (originating) company to one buying (destination) company that flow on each power line in a system. PTDFs allow operators, system planners, engineers, marketers, and regulators to determine the impact a specific transaction has on the power transmission line loads throughout the system. PTDF analysis is complicated by the fact that recent industry restructuring has allowed non-utility companies to share the transmission system that once was entirely controlled by a single utility company in each area.

Displays and Data Visualization Techniques

The current information visualization tools used by power system operators have evolved little beyond tabular component status displays and a static representation of the power grid, or one-line diagram, posted on the control room wall (Overbye, Wiegmann, Rich, & Sun, 2001). Recently, however, new visualization techniques have been proposed and implemented to overcome the problems and deficiencies of traditional power systems displays. One technique that has shown promise is the integrated one-line diagram, which is a computer-generated display that embeds dynamic component state information in a representation of the power grid. These displays act as mimic displays, using pictorial realism to show physical connections and limitations of important system components. They also capitalize on the predictions of the proximity compatibility principle by placing system topology and component state information in close proximity to provide better support for monitoring and fault resolution (Bennett & Malek, 2000; Wickens & Carswell, 1995).

Integrated one-line diagrams allow multiple methods of visualizing power systems data graphically, such as color contouring, three-dimensional figures, geographical displays, and motion. However, these expanded possibilities raise the concern for human factors issues related to information visualization and the possible cost/benefit trade-offs between different display formats. While the other methods listed above have been studied extensively, using motion to provide information about component states in an electrical system has been given comparatively little attention. In the present study, therefore, we examine the use of motion to convey power flow information to system operators.

Animation/Motion Displays

Motion can potentially aid visual search for faults and analysis of large-scale features in system data. Since attention can be directed to the fastest-moving items in a display (Ivry & Cohen, 1992; Rosenholtz, 1999), motion in a display can highlight search targets. In addition, studies have shown that expanding and contracting motion patterns are detected more easily than translating or random motion (Freeman & Harris, 1992; Geesaman & Qian, 1998). However, incoherent non-target motion can distract attention and slow search for target motion (Driver, McLeod, & Dienes, 1992).

Research on animation in mimic displays conducted by Bennett (1993; Bennett & Malek, 2000) has focused on the effectiveness of various methods of color table animation to indicate motion rather than on the potential advantages of animation over stationary cues. Studies in computer-based instruction have found benefits for animated displays over stationary displays (Park & Gittelman, 1995; Park & Hopkins, 1993). Park and Gittelman (1995) found that an animated display including moving arrows supported instruction in electronic troubleshooting better than static displays with and without arrows. In general, animation seems to enhance viewers' mental models of systems, suggesting that its benefits may also apply to real-time support of tasks.

Wiegmann, Essenberg, Overbye, and Rich (2002) conducted a preliminary study of motion in electrical power systems displays, measuring fault detection and resolution performance. They found that in trials with multiple faults, the time to identify the worst fault–identified by the highest digital number indicating transmission line power overload magnitude in all displays–was faster using a one-line diagram with digital values than with moving arrows indicating power flow direction and magnitude, possibly due to distraction caused by non-relevant motion. However, fault resolution times for multiple fault trials tended to be faster with the moving arrow display than with the digital display, perhaps because the moving arrows helped the participants determine power flow directions faster.

Purpose of the Present Study

The present study continues the investigation of motion in power systems displays and focuses on the potential costs and benefits of representing power flow with motion for monitoring, rather than fault resolution tasks. The preliminary study may have failed to find an advantage for motion in the fault identification task because motion did not adequately support search for faults. The configuration and motion of the arrows in the present study are expected to aid viewers specifically in directing attention to targets in a monitoring task.

Power transfer between utility companies represented by nodes in a large network was indicated by stationary arrows, arrows that moved at a uniform speed, and arrows whose speed was proportional to power transfer. We measured error rate, workload, and the time to select the buyer and seller nodes when they were connected directly or indirectly.

METHODS

Participants

Participants were 51 students recruited from Power Systems classes in the Department of Electrical and Computer Engineering at the University of Illinois, Urbana-Champaign. Participants were paid $12.00 for their participation, which required less than one hour. We screened two colorblind participants out of the analysis with a pre-experiment questionnaire, one each from the no-motion and proportional-motion display groups.

Apparatus

A modified version of Power World® Simulator software (Overbye et al., 1999) was used to simulate a high-voltage power system, running on a Dell Dimension XPS B800 computer with an 800-MHz Pentium III processor, 128 MB of RAM, and a 20-inch Dell Ultrascan P1110 monitor, with a mouse used for all input.

Display Types and Tasks

Each participant was assigned to a display group in which PTDF magnitude and direction on each transmission line were represented by stationary arrows (n = 16), moving arrows whose speed was uniform (n = 17), or moving arrows whose speed was proportional to the PTDF value (n = 16). In each display group, the size of the arrows was proportional to the PTDF value on each line. See Figure 1 for an illustration of the display. Each node represented a single utility, and each line connecting two nodes represented all of the individual power lines connecting the two utilities.

Participants were required to select the seller and the buyer nodes with the mouse, in either order, during each trial. The seller was uniquely identified by outbound arrows on each of the lines connecting it to other nodes (see node 58 in Figure 1), whereas the buyer was uniquely identified by inbound arrows on each line (see node 19 in Figure 1). All of the other nodes in each trial had both inbound and outbound arrows or no arrows on their connecting lines. If the seller and buyer were not directly connected to each other, the participants then selected any set of intermediate nodes that formed a path between the seller and buyer. For instance, nodes 61 (southern Iowa), 31 (eastern Missouri), and 50 (southern Missouri) define one possible path in Figure 1. There were no requirements in selecting the path nodes other than that they must form a continuous path between the seller and buyer. Each trial ended as soon as both the seller and buyer had been selected, and, for indirect connection trials, any set of the intermediate nodes selected formed a complete path between the seller and buyer. The participants were instructed to complete each trial as quickly and as accurately as possible.

Procedure

Each participant was randomly assigned to a display group and completed 4 practice trials and 50 experimental trials after reading the experimental instructions and watching the experimenter demonstrate successful completion of the first two practice trials. In each trial, the display initially showed no transfer; the network was displayed with no arrows on any of the lines. After a random interval up to 15 seconds, a power transfer occurred, indicated by the appearance of arrows on the lines with significant PTDF values, after which the participants were allowed one minute to complete the seller-buyer and path selection tasks. The seller and buyer were directly connected in 15 trials and indirectly connected in 35 trials. The same power grid was used across all trials and all display groups, and the same transactions occurred in the same order across the display groups. The time to select the seller and buyer, time to select the path, and number of erroneous clicks during the seller-buyer selection task in each trial were measured and recorded by the computer. In addition, the participants rated workload using the NASA Task Load Index (TLX).

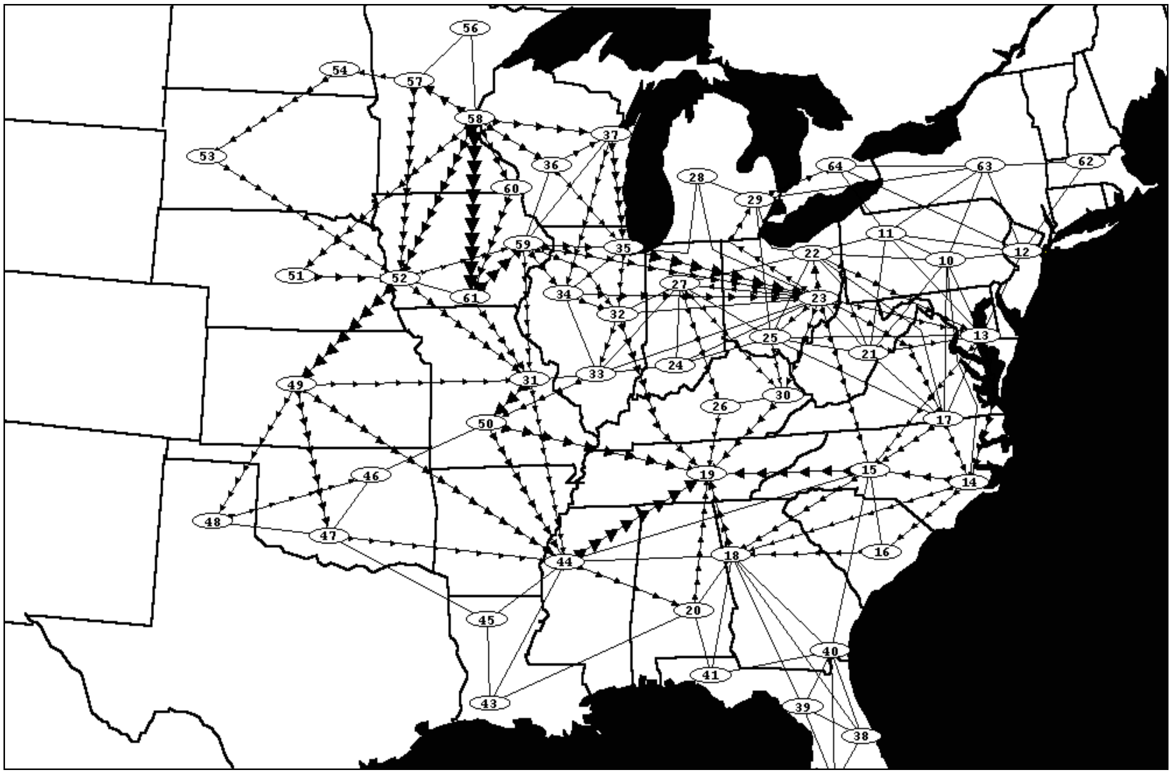

Figure 1. The PTDF display used in the experiment, showing a power transfer from node 58 (east-central Minnesota) to node 19 (central Tennessee). The size of the arrows on each line is proportional to the PTDF value, and the arrows either remain stationary, move at a uniform speed, or move at a speed proportional to the PTDF value.

RESULTS

Seller-buyer selection times and error rates were analyzed using 3 (Display Group: no motion, uniform motion, proportional motion) x 2 (Connection Type: direct, indirect) analyses of variance (ANOVAs). Results of the ANOVAs revealed main effects of display group, $F(2,46) = 12.5$, $p < .001$ (selection time), $F(2,46) = 5.66$, $p = .006$ (error rate), and connection type, $F(1,46) = 131$, $p < .001$ (selection time), $F(1,46) = 28.8$, $p < .001$ (error rate). The two-way interaction between display group and connection type was significant for seller-buyer selection time, $F(2, 46) = 4.97$, $p = .011$, and marginally significant for error rate, $F(2, 46) = 2.74$, $p = .075$. Figures 2 and 3 show the seller-buyer selection time and error rate interactions, respectively. Response times were faster and error rates were lower in the two displays with motion than in the no-motion display, and the effect was generally amplified in indirect connection trials. The participants in the proportional-motion display group had lower seller-buyer selection times and error rates than those in the uniform-motion display group, but the differences were not significant.

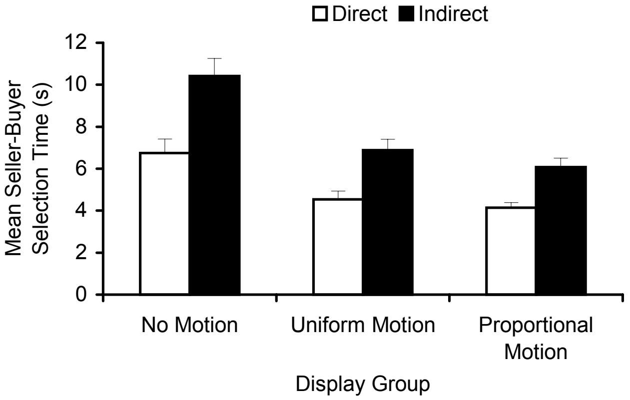

Figure 2. Mean buyer-seller selection times (+1 SE) by display group expanded across connection type.

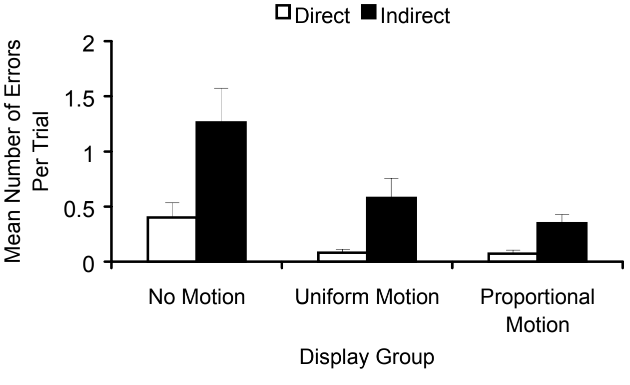

Figure 3. Error rate (+1 SE) by display group expanded across connection type.

No significant effect of display group was found when analyzing path selection times, $F(2, 46) = 0.240$, $p = .788$. There was a weak effect of display type on total NASA-TLX score, $F(2, 46) = 2.39$, $p = .103$, which was lowest in the proportional-motion display, followed by the uniform-motion display and static display, as shown in Figure 4.

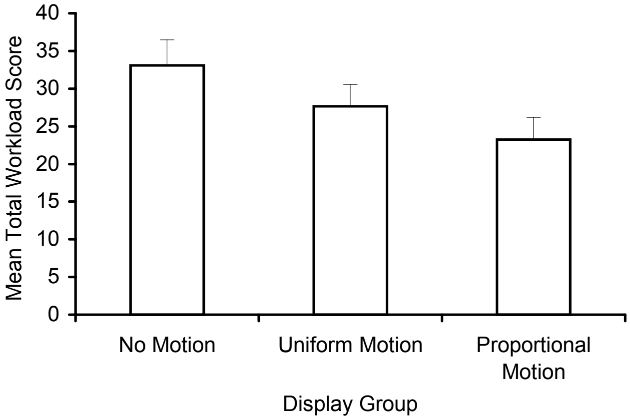

Figure 4. Total NASA-TLX workload scores (+1 SE) by display group.

DISCUSSION

Overview of Results

The results show a clear advantage for the motion displays in the seller-buyer selection task. The seller-buyer selection time was significantly faster with moving than with stationary arrows, and the increase in response time was lower with the motion displays when search difficulty, the separation between the seller and buyer, increased. Error rates were also lower with the motion displays and followed the same pattern as response time, eliminating the possibility of a speed-accuracy tradeoff. Participants subjectively rated workload as lower with the proportional-motion display than with the no-motion display, with the uniform-motion display falling between the other two. The lack of significant differences among the displays for the path selection task may primarily be due to its unstructured nature and simplicity.

Motion in Mimic Displays

The salience of motion may have helped the participants attend to the parts of the display most relevant to the seller-buyer selection task (Ivry & Cohen, 1992; Rosenholtz, 1999). In Wiegmann et al. (2002), who failed to find a significant advantage for moving arrows over stationary arrows in a search task, the fastest-moving arrows were not necessarily associated with the search target, and changes in motion speed throughout the display as faults occurred may have distracted from search for the target (Watson & Humphreys, 1998).

The motion of the arrows also simplified search by configuring uniquely for the seller and buyer, since they were the only nodes in the displays with all arrows flowing either out or in, creating emergent features (Wickens & Hollands, 2000, pp. 89, 98). Motion may have increased the salience of these configurations significantly, since humans are sensitive to expanding and contracting patterns (Freeman & Harris, 1992), perceive those patterns to be moving faster than linear motion (Bex & Makous, 1997; Geesaman & Qian, 1998), and are aided in grouping moving patterns through common fate (Driver & Baylis, 1989).

However, the incoherence of motion among the different lines in the proportional-motion display may have slowed search, as seen by Driver et al. (1992), and weakened the perception of common fate with respect to that in the uniform-motion display, perhaps accounting for the lack of significant differences between the two motion displays.

Implications for Display Design

Motion can be used successfully in mimic displays to aid understanding of the behavior of systems and aid monitoring if the display is configured such that motion provides information directly relevant to the user’s tasks and draws the user’s attention to the most relevant information. Task-relevant information can be highlighted with moving elements that configure into moving patterns that are easily grouped together and separated from the rest of the display, such as expansion and contraction (Ahlström & Börjesson, 1999; Meese & Harris, 2001). However, our results do not show a clear advantage for encoding flow magnitude with motion speed, suggesting that designers should ensure that the resulting incoherence of the motion will not overpower the highlighting advantage of faster motion and will not weaken emergent features defined by common fate. Overall, when search tasks are difficult and time is critical, our results indicate that displays designed such that motion creates emergent features can improve performance significantly over displays without motion.

ACKNOWLEDGEMENTS

This material is based on work supported by the National Science Foundation (NSF) through grant NSF DMI 00-60329, the Power Systems Engineering Research Council (PSERC), and the U.S. Department of Energy through its Consortium for Electric Reliability Technology Solutions (CERTS) program. Any opinions, findings, conclusions, or recommendations expressed are those of the authors and do not necessarily reflect the views of NSF, PSERC, or the Department of Energy.

REFERENCES

Ahlström, U., & Börjesson, E. (1999). Perceptual interference in the processing of superimposed motions. *Visual Cognition*, *6*(2), 129-144.

Bennett, K. B. (1993). Encoding apparent motion in animated mimic displays. *Human Factors*, *35*, 673-691.

Bennett, K. B., & Malek, D. A. (2000). Evaluation of alternative waveforms for animated mimic displays. *Human Factors*, *42*, 432-450.

Bex, P. J., & Makous, W. (1997). Radial motion looks faster. *Vision Research*, *37*, 3399-3405.

Driver, J., & Baylis, G. C. (1989). Movement and visual attention: The spotlight metaphor breaks down. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 448-456.

Driver, J., McLeod, P., & Dienes, Z. (1992). Motion coherence and conjunction search. *Perception and Psychophysics*, *51*, 79-85.

Freeman, T. C. A., & Harris, M. G. (1992). Human sensitivity to expanding and rotating motion: Effects of complementary masking and directional structure. *Vision Research*, *32*, 81-87.

Geesaman, B. J., & Qian, N. (1998). The effect of complex motion pattern on speed perception. *Vision Research*, *38*, 1223-1231.

Ivry, R. B., & Cohen, A. (1992). Asymmetry in visual search for targets defined by differences in movement speed. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 1045-1057.

Meese, T. S., & Harris, M. G. (2001). Independent detectors for expansion and rotation, and for orthogonal components of deformation. *Perception*, *30*, 1189-1202.

Overbye, T. J. (2000). Reengineering the electric grid. *American Scientist*, *88*(3), 220-229.

Overbye, T. J., Klump, R. P., & Weber, J. D. (1999). A virtual environment for interactive visualization of power system economic and security information. *Proc. IEEE Power Engineering Society Summer Meeting* (pp. 846-851). Piscataway, NJ: IEEE.

Overbye, T. J., Wiegmann, D. A., Rich, A. M., & Sun, Y. (2001). Human factors analysis of power systems visualizations. *Proc. of the 34th Annual Hawaii International Conference on System Sciences* (pp. 647-652). Piscataway, NJ: IEEE.

Park, O., & Gittelman, S. S. (1995). Dynamic characteristics of mental models and dynamic visual displays. *Instructional Science*, *23*, 303-320.

Park, O., & Hopkins, R. (1993). Instructional conditions for using dynamic visual displays: A review. *Instructional Science*, *21*, 427-449.

Rosenholtz, R. (1999). A simple saliency model predicts a number of motion popout phenomena. *Vision Research*, *39*, 3157-3163.

Watson, D. G., & Humphreys, G. W. (1998). Visual marking of moving objects. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 946-962.

Wickens, C. D., & Carswell, C. M. (1995). The proximity compatibility principle. *Human Factors*, *37*, 473-494.

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3rd ed.). Upper Saddle River, NJ: Prentice-Hall.

Wiegmann, D. A., Essenberg, G. R., Overbye, T. J., & Rich, A. M. (2002). Motion in mimic displays: Effects on the detection and diagnosis of electrical power system failures. *Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting* (pp. 1-5). Santa Monica, CA: Human Factors and Ergonomics Society.

Wiegmann, D. A., Rich, A. M., Overbye, T. J., & Zhang, H. (2001). *Effects of color contouring on the detection and diagnosis of voltage violations within electrical power systems* (Tech. Report ARL-01-10/SBC 01-263-DMI006032). Savoy, IL: University of Illinois, Aviation Research Lab.