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Motion as an Effective Flow Visualization Technique for Power Systems Monitoring and Control

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ABSTRACT

New power systems displays have been developed to aid operators in power system monitoring and control. In this study, we examined the use of motion as a potential enhancement of displays to illustrate power transactions in a large-scale network. The participants located and selected the buyer and the seller for a number of different transactions and then selected intermediate areas defining a path between the buyer and seller in trials where they were not directly connected. Participants performed the tasks using interactive displays indicating power transfer 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 stationary arrow display. Though we did not find significant differences between the two motion displays, there was a trend for better performance with the proportional-motion display. Tasks that are more difficult might reveal whether proportional motion is significantly better than uniform motion or whether the lack of coherence of motion with respect to the uniform motion display overpowers the advantages of proportional motion. We also failed to find differences among the displays for the path selection task; further experiments with more difficult path selection tasks might reveal if there are advantages for motion. Overall, our results indicate that motion used in displays to indicate flow among components or nodes in a system can significantly improve performance in tasks that require detection of specific patterns of flow.

INTRODUCTION

The interconnected electric power grid in North America is “one of the largest and most complex man-made objects ever built” and consists of “billions of individual components, tens of millions of miles of wires and thousands of individual generators” (Overbye, 2000, p. 220). To operate the system effectively, power system operators must interpret and integrate multiple parameters from each component in the areas of the power grid for which they are responsible (Overbye, Klump, & Weber, 1999; Wiegmann, Rich, Overbye, & Zhang, 2001). Furthermore, to stimulate competition, the power industry is restructuring to allow non-utility generators, brokers, marketers, and load aggregators to share the transmission system that once was entirely controlled by a single utility in each area, which has significantly increased the size of the network areas controlled by individual power system operators (Overbye, Weber, & Laufenberg, 1999). In addition, operators’ actions now affect not only the utility companies who employ them but also market participants across the continent, since power transactions are no longer restricted to those between adjacent utilities (Overbye, Sun, Wiegmann, & Rich, 2002). Consequently, without new visualization techniques to aid operators in monitoring and interpreting the significantly increased quantities of power grid data resulting from restructuring, they will be unable to adequately optimize the power grid for the many new market participants and protect the system from costly failures.

Some researchers and designers have suggested that motion can be used effectively to indicate power flow direction and magnitude, and motion has already been implemented in some control room displays (Klump, Schooley, & Overbye, 2002; Overbye, Weber, & Laufenberg, 1999). There have been few empirical studies on the effects that using motion in displays to indicate flow between components has on operator performance, though, which may not always improve performance. In this paper, we examine the potential advantages and possible disadvantages of aiding the power system operator with motion used in displays to indicate power transfer among utilities.

Prior to discussing the topics specific to the current study, however, an understanding of the power system operator’s tasks and the displays traditionally used to support those tasks is required. We then discuss some of the new visualization techniques that have been proposed for improving power system operator performance and previous empirical studies evaluating some of those techniques. The final sections of the introduction review the literature on the advantages and disadvantages of motion in displays and discuss a preliminary experiment on the use of motion in a power system display.

Power System Operator Tasks

Power system operators perform tasks typical of process control, which is characterized by controlled variables with long time constants derived from “analog, continuous processes,” the processes “consist of a large number of interrelated variables,” and they involve high risk (Wickens & Hollands, 2000, pp. 514-515). During normal system operation, the operator primarily monitors the system and adjusts the controls to keep certain variables within limits but will need to transition to a detection and diagnosis phase when unforeseen problems occur (Wickens & Hollands, 2000, p. 521).

The tasks power system operators perform fall generally into the two major process control categories of monitoring and contingency analysis. When faults occur, such as voltage violations or line overloads, operators diagnose the problems based on the information provided by their displays and then resolve the faults by adjusting generator output, opening new transmission lines, activating capacitors, or modifying other system parameters, following standard operating procedures or using troubleshooting procedures for novel problems (Wiegmann et al., 2001).

Some power system operators also monitor power transfer distribution factors (PTDFs), which show the percentages of an individual power transfer from one seller to one buyer 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 transmission line loadings throughout the system. The North American Electric Reliability Council (NERC) limits transactions to maintain system security when there is power flow congestion between one or more pairs of independently controlled areas, based partly on the PTDF values on the affected lines for each transaction (Overbye, Wiegmann, & Thomas, 2002, p. 28; Overbye, Wiegmann, Essenberg, & Sun, 2002). Because there are so many seller-buyer combinations in a large system, there must be an easy-to-interpret display of the PTDFs for any single transaction (Overbye, Wiegmann, Essenberg, & Sun, 2002). In the present study, we focus on performance in a PTDF monitoring task.

Traditional Displays

There has been little improvement in the displays used by power system operators to perform monitoring and fault resolution tasks with respect to traditional tabular displays, which show the status of the system components, used in combination with large, static, wall-mounted diagrams of the power grid incorporating colored indicator lights (see Figure 1 for examples of both traditional and new displays in a power system control room). Tabular displays list violations as text alarms, an ineffective format, especially when monitoring a large network, because important violations can be buried in a clutter of less important, unimportant, and redundant violations (Mahadev & Christie, 1994b). The result is that as the number of contingencies increases, the operator must search through more extraneous alarm messages, significantly increasing the operator’s workload as time becomes more critical. Therefore, given the larger networks and greater responsibilities of power system operators resulting from industry restructuring, presenting data in tabular and static wall-grid formats cannot support operators sufficiently in their tasks.

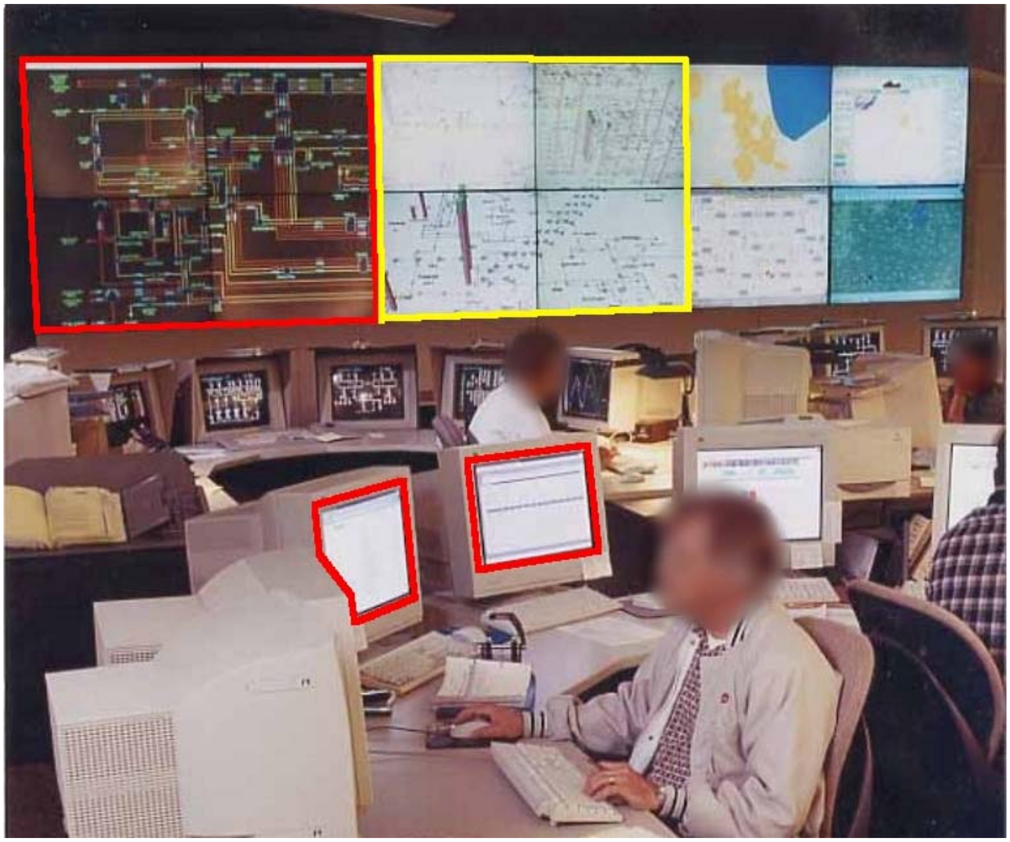


Figure 1. A power system control room with traditional tabular and static wall-mounted displays (outlined in red) and a new, three-dimensional graphical one-line display (outlined in yellow).

Traditional displays also include one-line diagrams of power substation data, schematic diagrams presented on computer-generated character graphics displays showing electrical buses as individual lines and indicating their connections to generators, capacitors, and other buses. These displays cannot be scaled up to show the status of the entire network due to the limitations of character graphics (Christie, 1994). In response to this limitation, most power control rooms have been upgraded with full graphics displays, which allow graphics to be built from individual pixels rather than the specialized characters to which designers were limited in character graphics displays (Christie, 1994). Initially, though, most full graphics displays simply consisted of relocatable windows containing traditional character graphics displays, and operator performance failed to improve (Christie, 1994).

In supporting tasks that require rapid assessment of the interrelationships among the multiple subsystems throughout a large power network and the state of the system as a whole, traditional presentation methods are less than ideal. Enabling operators to perform at their full potential in these tasks requires new visualization techniques that take advantage of the capabilities of full graphics displays (Christie, 1994).

New Visualization Techniques

Researchers and designers have proposed and implemented a variety of graphical display techniques aimed at improving operator performance. The techniques relevant to PTDF monitoring tasks are presented below.

Integrated one-line diagrams. Full graphics displays allow the integration of dynamic digital values and new graphical representations with traditional one-line diagrams (Overbye, Sun, Wiegmann, & Rich, 2002; Overbye, Wiegmann, Rich, & Sun, 2001) (see Figure 2). Co-locating representations of power system components and component state information in integrated one-line displays is intended to aid operators in analyzing system data and resolving contingencies, enabling operators to interpret the results of actions on the network more easily in real time by capitalizing on the predictions of the proximity compatibility principle (Bennett & Malek, 2000; Rich, Wiegmann, & Overbye, 2001b; Wickens & Andre, 1990; Wickens & Carswell, 1995; Wiegmann et al., 2001).

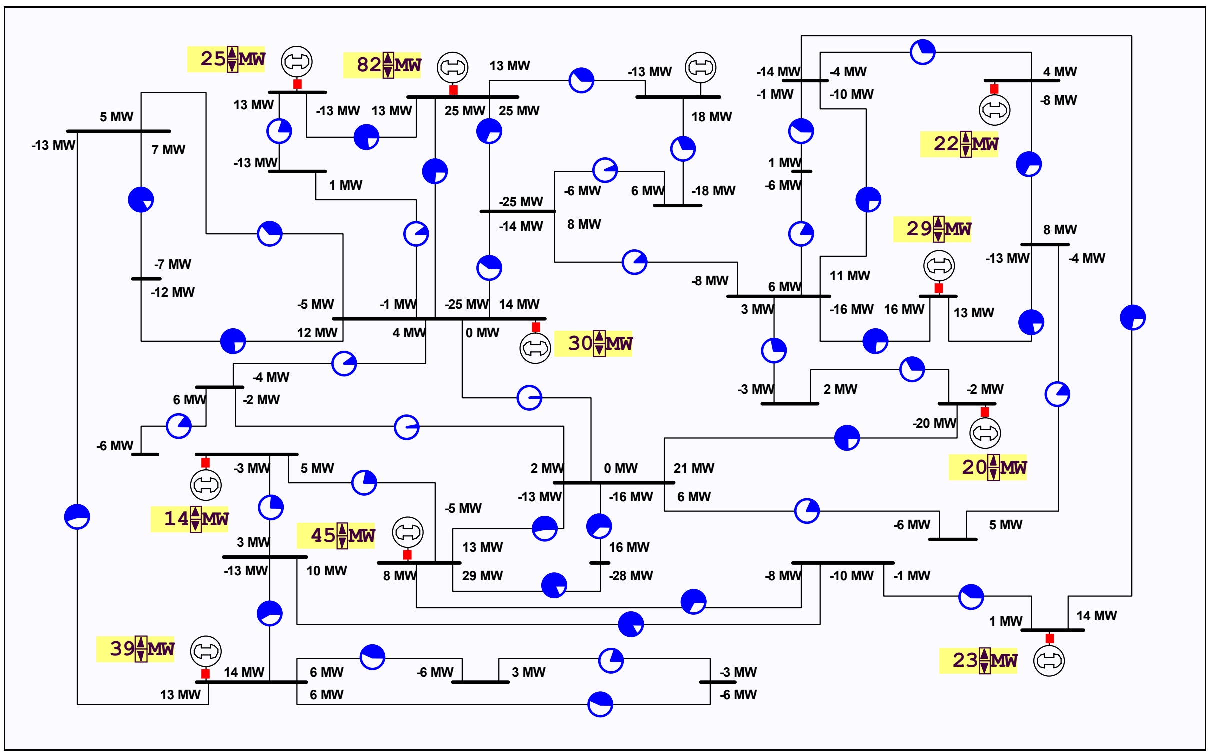


Figure 2. An integrated one-line diagram with power flow on transmission lines indicated by dynamic digital values and percentage loads indicated graphically by pie charts.

Integrated one-line diagrams can also be classified as mimic displays, which support process control by representing a system at the level of its physical function (Bennett, 1993; Bennett & Malek, 2000; Hollan, Hutchins, McCandless, Rosenstein, & Weitzman, 1987). They depict important components, systems, or subsystems as they appear in the physical world, using pictorial realism to show the components' physical connections and operating limits (Rasmussen, 1986, p. 17), and thus potentially provide better support for detection and diagnosis of system faults (Bennett & Malek, 2000). Kieras (1992) suggests that mimic displays that explicitly show the states of internal system components and clearly indicate failures of components support both normal operation and diagnosis of problems in complex systems.

In a study comparing performance with traditional displays and integrated one-line diagrams, Overbye, Sun, Wiegmann, and Rich (2002) found that participants acknowledged violations in a simulated 30-bus system faster with a tabular display of power system component information accompanied by a static paper diagram of the system topology than with dynamic integrated one-line diagrams, which indicated bus voltage with either digits or color contours. They attributed this to the simplicity of searching for violations in a single column in the tabular display relative to searching through the more disorganized two-dimensional data in the one-line diagrams. However, participants solved the voltage violations, which required activating capacitors electrically near the violations, faster with the integrated one-line displays. The authors concluded that this was because the greater proximity of the system topology and component state information supported faster information integration.

Graphical representation of variables. Representing variables graphically, rather than with numbers, can improve viewers' abilities to see relationships among the data (de Azevedo, de Souza, & Feijó, 1996; Liu & Wickens, 1992). Some applications to power systems displays that have been suggested are time series graphs to illustrate time-dependent relationships (Mahadev & Christie, 1994b), pie charts to represent phase angle (Liu & Qiu, 1998), color-coded bars to represent bus voltages (Mahadev & Christie, 1994a), color-coded pixels to represent bus voltages in large-scale displays (Mitsui & Christie, 1997), color contouring to speed identification of bus voltage violations (Overbye, Sun, Wiegmann, & Rich, 2002; Rich et al., 2001b; Wiegmann et al., 2001), radar charts to show power buying and selling levels and tie line limits (Thiyagarajah, Carlson, Bann, Mirheydar, & Mokhtari, 1993), and arrows to indicate power flow on transmission lines, whose width (Mahadev & Christie, 1994a) or speed (Wiegmann, Essenberg, Overbye, & Rich, 2002) is proportional to power flow.

Wiegmann et al. (2001) studied the use of color contours in power system displays and found that participants acknowledged the worst bus voltage violation in a simulated 118-bus system with contour-only and digital-plus-contour integrated one-line displays faster than with a digital-only integrated one-line display in trials with more than eight initial violations. They concluded that the contours helped direct the participants' attention to the worst violations by highlighting them with warmer colors. Conversely, participants solved the voltage violations—by activating capacitors electrically near the violations—more slowly and using more capacitors with the contour-only and digital-plus-contour displays than with the digital-only display. Apparently, contours aided attention allocation in visual search, but the added clutter and obscuration of capacitors detracted from performance in the solution task.

Geographical displays. Geographical displays show power system components and connections in their geographical locations on a map (see Figure 3). These displays can be panned, zoomed, and decluttered based on zoom level. Research in the field of Geographical Information Systems (Frank, 1993) suggests that displaying data in a geographical context should allow operators to integrate multiple sources of spatially-situated information, potentially improving their ability to see relationships and trends among power system variables and component states (Liu & Qiu, 1998; Mahadev & Christie, 1994b). In addition, geographical displays are mimic displays and offer the potential advantages derived from pictorial realism and proximity compatibility described above in the integrated one-line diagram sub-section. When displaying data over a large geographic region, however, designers often use data integration techniques to reduce clutter.

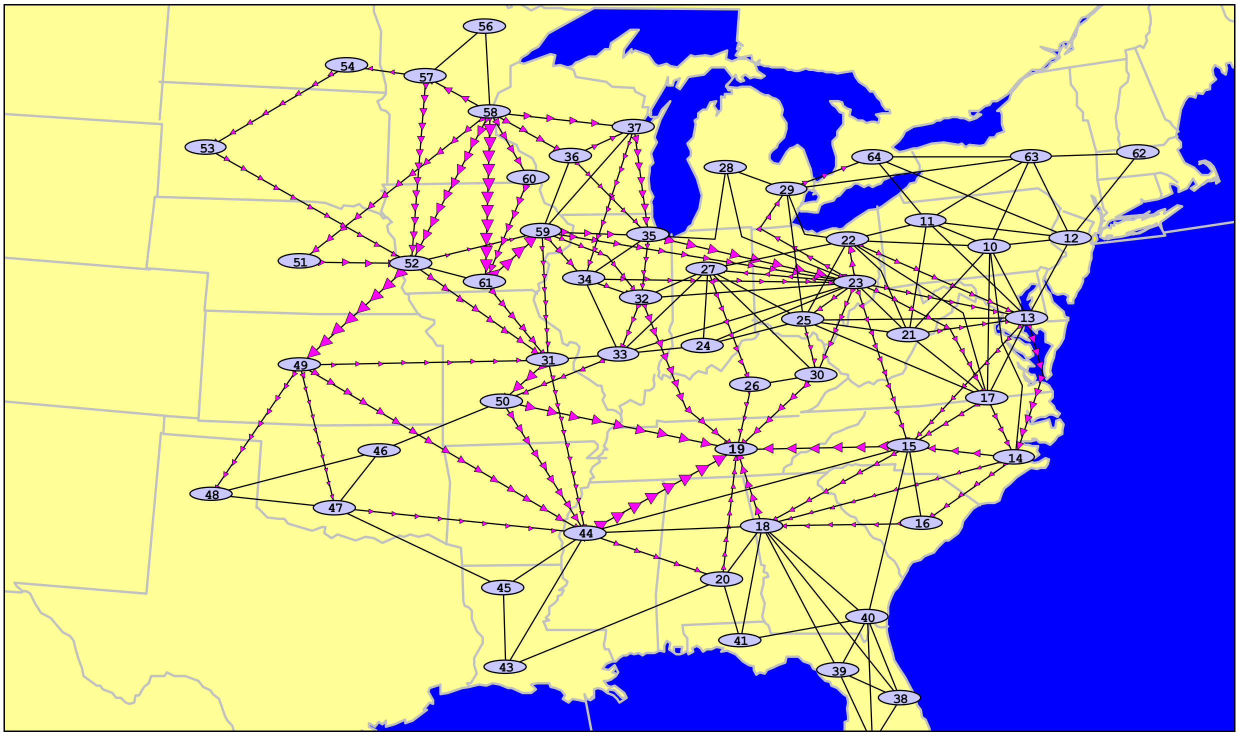


Figure 3. An example of the geographic PTDF display used in the present study, prior to selecting any nodes, showing a power transfer from node 58 to node 19. Data aggregation has been used to simplify the display and emphasize power transfer between entire areas rather than individual buses.

Data aggregation. Data aggregation simplifies the display of power networks over a large geographic region spanning a number of individually owned areas (see Figure 3). Each area is represented as a single object with single lines connecting it to each of its neighboring areas. Each line represents the collection of all of the individual system branches that connect the two areas, which is called a flowgate and behaves as a single power line whose power flow capacity is equal to the combined limitation of the individual branches (Overbye, Weber, & Laufenberg, 1999). However, data aggregation should be used carefully, since the loss of information about the states of individual transmission lines and components could hide important contingencies or developing problems.

Motion. Power systems engineers have used motion in displays for a variety of applications. Overbye, Weber, and Laufenberg (1999) suggested that animating color contours would aid identification of developing problems in a power network. Kobayashi, Okamoto, Tada, Yamada, and Sekine (1998) described a method of visualizing the dynamic characteristics of power systems by animating the states of buses through time with the values of phase angle, voltage, or power flow presented graphically by size or position on a graph. Wiegmann et al. (2002) studied the use of moving arrows to represent power flow on transmission lines, a visualization technique that has already been implemented in a power system control room (Klump et al., 2002). Motion in displays has the potential to improve operator performance by developing better mental models of system operation and in drawing their attention to problems.

To date, the evaluation of motion in power systems displays has received little attention relative to other visualization techniques. A previous study and a review of the human factors literature suggest that there are both advantages and disadvantages to the use of motion in power systems displays.

Motion

In other contexts, motion has shown potential to aid search for items, such as faults, in displays and to aid an operator's understanding of the state of a system. We first discuss the advantages and disadvantages of directing attention with motion, then discuss perception of expanding and contracting patterns—which are relevant to the identification of power sellers and buyers in the present study—followed by perceptual organization of moving elements and mental model enhancement with motion.

Directing attention. Motion can direct an operator's attention to areas of a display relevant to a particular task. For instance, moving arrows can draw attention to a power line whose power load limit has been exceeded. Studies indicate that attention can be selectively directed to only the moving items in a display, even if they move in multiple directions, and that search for a single feature among the moving items is parallel (McLeod, Driver & Crisp, 1988; McLeod, Driver, Dienes, & Crisp, 1991). In addition, search for a moving item among items moving at a slower speed is parallel (Ivry & Cohen, 1992). Rosenholtz (1999) developed a model based on the idea that judging the salience of an item due to motion is equivalent to a parametric test for outliers in a statistical distribution: On a two-dimensional plot of velocity, the distance between the point representing the velocity of the target and the mean of the distribution of distractor velocities is proportional to salience. Since a moving target's velocity lies outside the mean distribution of velocities of stationary distractors, the model predicts that it will be salient. The model also shows that targets that move faster than distractors will be salient. A number of studies have confirmed that as target speed increases, search time and reaction time decrease (Hohnsbein & Mateef, 1992; Ivry & Cohen, 1992; von Mühlenen & Müller, 2000; Ware, Bonner, Knight, & Cater, 1992).

Motion and dynamic changes might hinder performance, though, if incorporated into task-irrelevant areas of displays. Navon's (1977) principle of global precedence can be applied to motion, suggesting that all of the moving items in a display will be processed before attention can be directed to a subset of the moving items that are relevant to a task. For instance, Verghese and Stone (1995) found that the speed difference threshold for detecting which of two intervals had gratings moving at a higher speed increased as the number of distractor gratings moving at a lower speed increased.

The coherence of motion among multiple items also has an effect on search speed. McLeod et al. (1991) found that search for a fast target among slower distractors was slower if all of the items moved in heterogeneous directions than if they moved in the same direction. Driver, McLeod, and Dienes (1992) found that search for an oscillating target was slowed in the presence of distractors oscillating incoherently in a different direction, and search was even slower when the target and the distractors oscillating in the target direction were also incoherent. Other studies have found, however, that distraction caused by non-target motion can be mitigated if the moving distractors share a common feature, such as color, that distinguishes them from a moving target (Olivers, Watson, & Humphreys, 1999; Watson & Humphreys, 1997, 1998).

Expanding and contracting motion. The results of some studies suggest that there are specialized mechanisms in the human visual pathway sensitive to expanding and contracting patterns and that they are processed differently than purely translating patterns. Experiments showing that detection of translation, rotation, expansion/contraction, and deformation in random dot displays is hindered by a second complex orthogonal motion distractor pattern but not with random noise distractors suggest the presence of specialized independent mechanisms for detecting those four complex motion patterns (Ahlström & Börjesson, 1999; Meese & Harris, 2001). Burr, Badcock, and Ross (2001) suggest further decomposition into two kinds of specialized detectors, sensitive either to radial or circular motion, for sensing complex motion, a conclusion based on experimental results showing that motion coherence sensitivity was not increased significantly by combining radial and circular motion and that radial masks did not significantly affect circular motion detection and vice versa.

Research has also shown that expansion and contraction are detected more easily and are perceived to be moving faster than translation at the same actual speed. Freeman and Harris (1992) found that motion in brief presentations of expanding and rotating random dot patterns was detected more easily than in displays of translating or random motion. A study that compared the perceived speed of translating and radial motion in textured gratings found that radial motion was perceived to be faster than translation of the same speed by as much as 60 percent (Bex & Makous, 1997). The authors explained that this might have been because the radial stimulus appeared to be moving in depth, resulting in a greater perceived distance of travel per unit time. Geesaman and Qian (1998) also found that radial motion of limited lifetime random dot stimuli was perceived to be faster than translating motion. However, Ahlström and Börjesson (1996) found that translation embedded in a random dot pattern was detected more easily than expansion or contraction and suggested that Freeman and Harris's method of displaying translation without noise motion in the background made the task much harder since the viewers did not have any optical references to allow detection of relative motion. Whether or not expanding and contracting motion is easier to detect than translating motion, it appears that expanding and contracting patterns can easily be differentiated from simple translation both due to complex motion detectors and because the perceived speed is faster than that of translating motion at the same true speed.

In some situations, there also appear to be differences in the perception of expanding versus contracting motion. Geesaman and Qian (1998) observed that the perceived speed of contraction was slightly faster than expansion at the same true speed. However, Takeuchi (1997) found that visual search using luminance-varied gratings was parallel for an expansion target among contraction distractors but serial for a contraction target among expansion distractors. Thornton and Gilden (2001) found that sign acquisition was parallel for contraction and expansion in circular patches of moving texture against a textured background, but they failed to find an asymmetry between expanding and contracting targets. Braddick and Holliday (1991) found that search for both cyclically contracting square contours among expanding square contours and for expanding targets among contracting distractors was slow and serial. In addition, they found that search for horizontal translating motion of a vertical line among distractors moving in the opposite direction was parallel, and suggested that their results differed from other studies on the perceived speed of expanding/contracting motion because the other studies did not use a search paradigm and because a specific organization of local optical detectors are required for pop-out in search that is not present for divergence-sensitive units (Braddick, 1993).

Takeuchi contended that Braddick and Holliday's results may have been confounded by the noise introduced when the expanding and contracting squares cycled from maximum to minimum size and vice versa, briefly giving the perception of the orthogonal motion direction, and that though the same noise was present for the translating targets—for which search was parallel—signal-to-noise ratios for translation and expansion/contraction may differ. If there is a difference in the difficulty of detecting or finding expansion and contraction, it is unclear if the effect is large enough to be practically significant and how the effect is modified by different presentation methods.

Perceptual organization. Motion can also aid perceptual organization in displays through the Gestalt principle of common fate. Studies have found that grouping by common fate, in which separate objects moving in similar directions at similar speeds are perceived as a single object, overrides grouping by spatial proximity (Driver & Baylis, 1989; Valdes-Sosa, Cobo, & Pinilla, 1998). Attention can also be directed to stimuli moving in only one direction in the presence of distractors moving in a different direction (McLeod et al., 1991). Uttal, Spillman, Stürzel, and Sekuler (2000) showed that coherent motion could be detected, even if individual items' trajectories diverged, converged, or crossed, as is the case with expanding and contracting motion. These studies all suggest that the expanding and contracting patterns associated with the targets in the displays in the current study can be perceptually grouped as single objects, even in the presence of nearby and interspersed motion not associated with the targets. Furthermore, the expanding and contracting patterns in the two displays with motion in the present study comprise emergent features, resulting in a configural display arrangement (Wickens & Hollands, 2000, pp. 89, 98).

In a review of a number of studies on divided and focused attention in displays, Bennett and Flach (1992) stressed the importance of semantic mapping from the domain to the display and concluded that configural displays, in which perceptual dimensions maintain their unique perceptual identity but create new emergent features when they interact, can reduce both divided and focused attention demands. Configural displays support both detection and diagnosis tasks because the operator can attend to either the high-level constraints of the system reflected in the emergent features of the display or the low-level data represented by the individual display elements (Bennett & Flach, 1992).

Mental models. The STEAMER project (Hollan et al., 1987; Hollan, Hutchins, & Weitzman 1984) incorporated motion in mimic displays to aid understanding of dynamic system behavior. Referring to a series of experiments studying animation in mimic displays (Bennett, 1993; Bennett & Madigan, 1994; Bennett & Malek, 2000; Bennett & Nagy, 1996), Bennett (1993) claimed that "[animated mimic] displays can improve real-time performance by (1) contributing to an individual's ability to assess current system state and the causal factors that underlie that state, (2) illustrating alternative system resources that can be used to avoid or recover from the violation of system goals, and (3) providing immediate feedback regarding the effectiveness of control input" (p. 676). Bennett and Malek (2000) asserted that "Discrepancies between the expected and actual flow patterns should make faults easier to detect because of the operators' sensitivity to motion" (p. 448). However, these studies 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.

Research in computer-based instruction has revealed significant benefits for animated displays with respect to stationary displays (Baek & Layne, 1988; Blankenship & Dansereau, 2000; Park & Gittelman, 1992, 1995). Rieber, Boyce, & Assad (1990), though not finding significant effects for animation, noted that it aided information organization and retrieval. Park and Hopkins (1993) noted that graphically representing invisible behaviors of a system is important in helping users develop mental models and that representing those behaviors may be difficult with static displays. Park and Gittelman (1995) found that participants who were instructed in electronic troubleshooting with displays indicating current flow, circuit device behavior, and troubleshooting procedures using animation solved problems after fewer attempts and were better able to visualize motion in electronic circuits than those instructed with static displays that either indicated current flow with arrows or did not indicate current flow at all. However, Tversky and Morrison (2002) point out that many of the computer-based studies mentioned above fail to isolate animation as an effect but add critical information in the animated displays not present in the static displays and that few, if any, studies have truly found an advantage for learning with animation. They caution that to be truly useful for learning, animation should be used to show change in time, the sequence of continuous, rather than discrete events, or "causal flow" (p. 258), and that often a well-conceived static diagram works just as well. The authors suggest that current evidence shows that animation is better used for real-time visualization of change.

Preliminary Study on Motion in Power Systems Displays

Wiegmann et al. (2002) conducted a preliminary study of motion in displays, measuring fault detection and resolution performance—monitoring and contingency analysis, respectively—with one-line diagram displays of a 30-bus power system. The benefits found for motion were minimal. In trials with multiple violations, participants acknowledged the worst transmission line overload faster when using a one-line diagram with only digital values than when using a one-line diagram with moving arrows representing power flow on transmission lines; performance with a stationary arrow display lay between the two other displays. The disadvantage for the moving arrow display may have been due to distraction caused by dynamic changes in arrow size and speed throughout the display as contingencies occurred. However, there was a trend toward faster solution times in multiple violation trials with the moving arrow display than with the digital display. Performance with the stationary arrow display lay between the two but closer to the performance level with the moving arrow display. Evidently, the moving arrows helped the participants determine power flow directions faster, resulting in the advantage for the moving-arrow display. The failure to find a significant advantage for the moving arrow display over the stationary arrow display may have been due to distraction caused by irrelevant motion in the moving arrow display or because the task difficulty was not high enough.

The present study continues the investigation of motion in power systems displays and focuses on the potential costs and benefits of using motion to represent power flow for PTDF monitoring tasks. The failure of the preliminary study to find an advantage for motion in the acknowledgement task was probably because motion did not adequately support search for violations. The configuration and motion of the arrows in the present study are expected to aid viewers specifically in directing attention to the targets in the monitoring task.

Purpose of the Present Study

In the present study, we compared participants' performance in searching for the buyer and seller in displays with stationary arrows whose size was proportional to PTDFs, moving arrows whose size was proportional to PTDFs, and moving arrows whose size and speed were proportional to PTDFs. In addition, the buyer and seller were directly connected in some trials and separated by at least one intermediate area in the rest. Participants were required to select any path connecting the seller and buyer when they were not directly connected.

We expect that displays representing PTDFs with moving arrows will support faster and more accurate buyer-seller search performance than the display using stationary arrows. The largest PTDFs—and thus the largest arrows in the uniform-motion display and the fastest-moving and largest arrows in the proportional-motion display—are often located near the buyer and seller for any given transaction, highlighting the areas of interest. The salience of faster-moving targets in the proportional-motion display should further aid search for both the buyer and the seller. Because arrows are not shown on lines on which the PTDF is very small, we also expect motion to help limit search for the buyer and seller to only the areas with significant PTDF values.

Motion also configures the arrows into orthogonal emergent features (i.e., expansion vs. contraction) surrounding the buyer and seller, which, in combination with grouping the arrows by common fate, should help users narrow their search to the areas in the displays where most of the arrows are either flowing in or out, rather than in both directions. Grouping by common fate may be more difficult in the proportional-motion display, however, because the arrows on different lines radiating from the buyer and seller can move at different speeds, which may counteract the advantage stated above of faster motion "highlighting" lines with high PTDF values.

Motion also has the potential to reduce path selection time. Large PTDF values tend to occur on the various lines connecting the buyer and the seller, so that the highlighting effect of moving arrows that are fast and/or large may give the motion displays an advantage and the proportional-motion display an advantage over the uniform-motion display. Enhancement of mental models may also give the motion displays an advantage by supporting assessment of the current state of the system and its causal factors, as mentioned by Bennett (1993), through improvement of the user's understanding about how a transaction affects power flow in the network. However, we do not expect to see large effects of display type on path selection time due to the simplicity of the task and because power flow loops through the entire network for any given transaction, contributing to the possibility of distraction caused by large PTDF values on lines that are not on or near a direct path between the buyer and seller.

Workload should follow a pattern similar to response times and accuracy. Just as the moving arrow displays are expected to support faster and more accurate performance, we expect that the participants will not have to use as many mental resources to achieve performance with those displays. The motion-speed-highlighting advantages with the proportional-motion display may also produce lower workload ratings than with the uniform-motion display.

METHODS

Participants

The experiment included 51 participants, 43 men and 8 women, who were recruited from power systems classes in the Department of Electrical and Computer Engineering at the University of Illinois, Urbana-Champaign. Using an entrance questionnaire including a question that asked if the participants had any form of color blindness, we screened two male participants out of the analysis, one each from the no-motion and proportional-motion display groups. All participants either had completed or were currently enrolled in at least one power systems course. The mean number of power systems courses taken currently or in the past by the participants was 1.3, with a range of 1 to 4 courses. The participants' median age was 21, ranging from 18 to 30. They were each paid $12.00 for their voluntary participation.

Computer Software and Apparatus

A modified version of PowerWorld® Simulator software (Overbye, Klump, & Weber, 1999; Rich, Wiegmann, & Overbye, 2001a) was used for the experiment, which allowed configuration and representation of local utilities, equivalent transmission lines, and power transfer in the power system simulation. The software was run 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.

Power System Simulation and Tasks

The software simulated a high-voltage electric power system that roughly approximated the power grid in the eastern United States by dividing the grid into sections owned by different utility companies, each indicated by a single node (see Figures 3 and 4). The grid is actually much more complex and completely interconnected, but this representation is useful for visualizing power transactions between the local utilities that own the individual wires and generators. During each trial, power transfer between one utility selling power and one utility buying power were shown by encoding the PTDFs on each line with arrows whose speed of movement and/or size were proportional to the magnitude of the PTDF on that line.

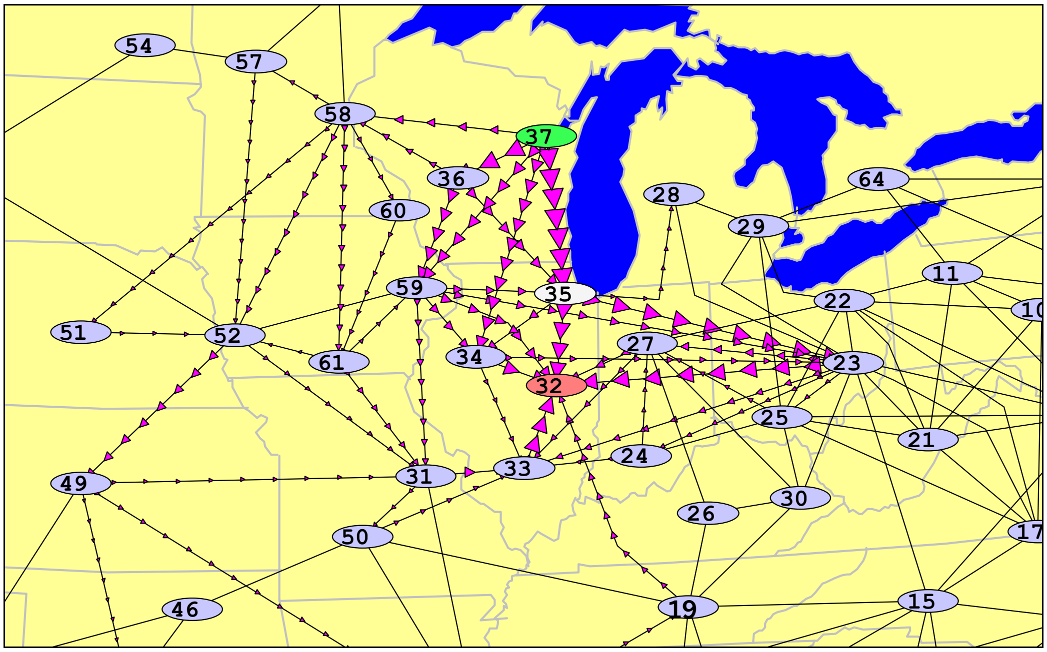


Figure 4. Close-up showing the completion of practice trial two. The magenta arrows indicate the direction of power transfer, and their speed of movement and/or size indicates the magnitude of the power transfer distribution factor (PTDF) for each line. The green node is the seller, the red node is the buyer, and the white node is the selected path between the seller and buyer.

Participants were required to perform up to two consecutive tasks in each trial. First, they searched for and selected the buying utility and the selling utility, in any order. The buying utility was indicated by inbound arrows on all the lines connecting it to other utilities, while the selling utility was indicated by outbound arrows on all the lines connecting it to other utilities. Since the power does not always flow directly from the seller to the buyer but loops throughout a large portion of the network, there were several utilities located on loops between the buyer and seller in each trial with both inbound and outbound arrows on their lines, increasing the difficulty of finding the buyer and seller. When selected, the seller's node turned from gray to green, the buyer's node turned from gray to red, and no change occurred if a node was selected that was neither the buyer nor the seller. If the buyer and seller were directly connected by an equivalent transmission line, the trial ended as soon as they were both selected. Otherwise, the buyer and seller nodes remained red and green, and the participant's second task was to select any set of utilities that formed a path between the buyer and seller. The participants could select any nodes other than the buyer and seller—each newly selected node turned from gray to white—and the trial ended as soon as any subset of the selected nodes formed a complete path between the buyer and seller.

Display Types

Participants completed the experimental task using one of three display types. Each display showed the utilities in the eastern United States connected by equivalent transmission lines (see Figures 3 and 4) with PTDF magnitude and direction on the transmission lines indicated by:

stationary arrows whose size was proportional to the magnitude of the PTDF on each line, moving arrows whose size was proportional to the magnitude of the PTDF on each line and whose speed was uniform throughout the display, or moving arrows whose size and speed were proportional to the magnitude of the PTDF on each line.

Procedure

Phase 1: Group assignment and instructions. Each participant was randomly assigned to a display type. The three display groups were the no-motion group (n = 16), the uniform-motion group (n = 17), and the proportional-motion group (n = 16). Participants began the experiment by completing a consent form (see Appendix A) and providing basic demographic and education information (see the questionnaire in Appendix B). They were then provided specific written instructions about the display and the tasks to complete during the experiment (see Appendix C). Each participant was asked to read the instructions completely and inform the experimenter when ready to proceed or ask questions if any came up.

Phase 2: Trials. Each participant was administered 4 practice trials and 50 experimental trials. The 50 experimental trials were divided by buyer-seller connection type into 15 trials where the buyer and seller were directly connected to each other by an equivalent transmission line and 35 trials where the buyer and seller were connected indirectly, with at least one utility node in the shortest path between them. The experimenter demonstrated successful completion of the first two practice trials before the participant began the first practice trial. At the beginning of each trial, the network was displayed with no power transfer, and after a random interval between 2 and 12 s, power transfer was indicated by the appearance of arrows on the lines with significant PTDFs. The PTDFs on each line were identical across the three display groups in each trial, but the buyer, seller, and PTDF distribution varied from trial to trial. The participants were allowed 60 s to complete each experimental trial. When the buyer and seller had been selected, and, if they were not directly connected, a path connecting them had been selected or time had run out, the trial ended. A dialog box then appeared informing the participant of the outcome of the trial, and the participant clicked "OK" when ready to proceed to the next trial or to quit the program in the case of the final trial.

Phase 3: Post-experimental questionnaire and debriefing. After the final trial, the participants completed a post-experimental questionnaire, which included the NASA Task Load Index (TLX) subjective workload assessment (see Appendix D), were given a debrief sheet explaining the general purpose of the experiment, and were dismissed.

RESULTS

Dependent Measures

Performance was measured by response times, error rate, the number of nodes in each selected path between buyer and seller, the order of selection of the buyer and seller, and workload. Response times measured were the time from the appearance of PTDFs in each trial for participants to select both the buyer and the seller and the time following selection of the buyer and seller to select the path between the buyer and seller in trials where they were not directly connected. Error rate was measured by the number of nodes selected per trial that were neither the buyer nor the seller during the buyer-seller selection task. The number of nodes selected during the path selection task was counted for trials where the buyer and seller were not directly connected. The order of buyer and seller selections was analyzed to reveal possible differences in the difficulty of finding the buyer and seller and to assess the effect of display format. Finally, workload was measured with the NASA-TLX subjective workload assessment.

Response Times

The mean time per trial required to select both the buyer and the seller was calculated, the time to complete the buyer-seller selection task. The times to complete the buyer-seller selection task were analyzed using a 3 (Display Group: no motion, uniform motion, proportional motion) x 2 (Connection Type: direct, indirect) analysis of variance (ANOVA). *T* tests were used to determine significant differences between individual data points.

Figure 5 shows the mean time to complete the buyer-seller selection task as functions of display group and connection type. The results of the ANOVA showed a significant main effect of display group, $F(2, 46) = 12.5$, $p < .001$, revealing a motion advantage. As illustrated in Figure 5a, participants in the no-motion display group took longer to select the buyer and seller ($M = 9.31$, $SD = 3.08$) than those in the uniform-motion ($M = 6.18$, $SD = 1.95$) or proportional-motion ($M = 5.50$, $SD = 1.42$) groups. *T* tests showed that the differences in times to complete the buyer-seller selection task between the no-motion and uniform-motion groups, $t(31) = 3.52$, $p = .001$, and between the no-motion and proportional-motion groups, $t(30) = 4.50$, $p < .001$, were significant, but that the difference between the uniform-motion and proportional-motion groups was not significant, $t(31) = 1.13$, $p = .266$. There was also a significant main effect of connection type, $F(1, 46) = 131$, $p < .001$. Figure 5b shows this proximity benefit. Participants across all display groups had faster buyer-seller selection task completion times when the buyer and seller were directly connected ($M = 5.13$, $SD = 2.22$) than when they were indirectly connected ($M = 7.78$, $SD = 3.12$).

Figure 6 shows buyer-seller selection task completion times as a function of display group expanded across connection type. The ANOVA results showed a significant two-way interaction between display group and connection type, $F(2, 46) = 4.97$, $p = .011$. The interaction is illustrated by the enhancement of the motion advantage for indirect connection trials; the differences between the no-motion display and the two motion displays were generally larger for indirect connection trials. Tables 1, 2, and 3 show descriptive statistics and the results of the t tests between all of the data points. All of the differences except those between the two motion display groups for both direct and indirect connection trials contributed to the interaction.

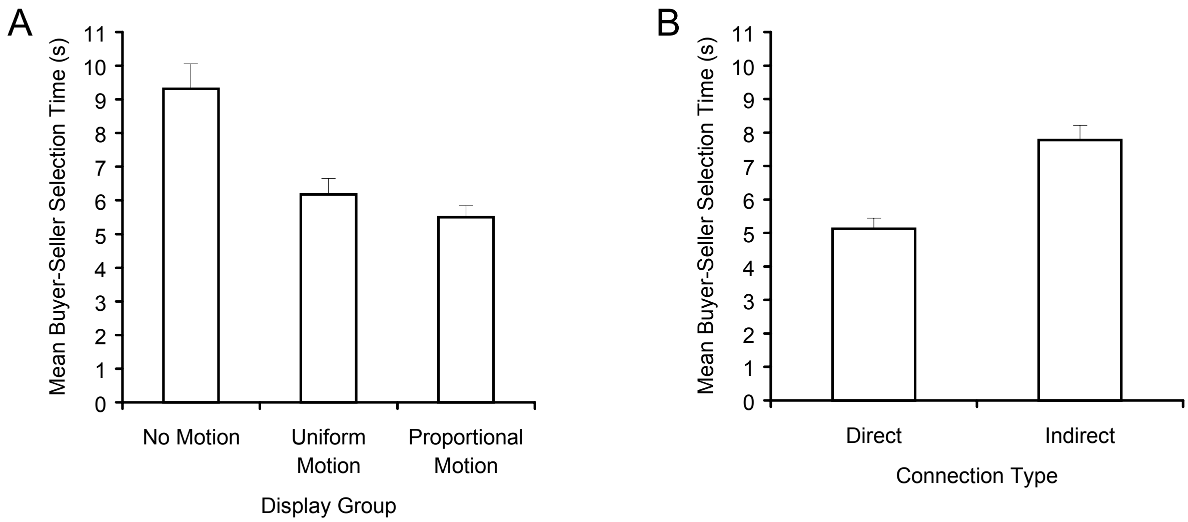


Figure 5. Main effects of (a) display group and (b) connection type on mean buyer-seller selection time, the motion advantage and proximity benefit, respectively. Error bars represent standard error.

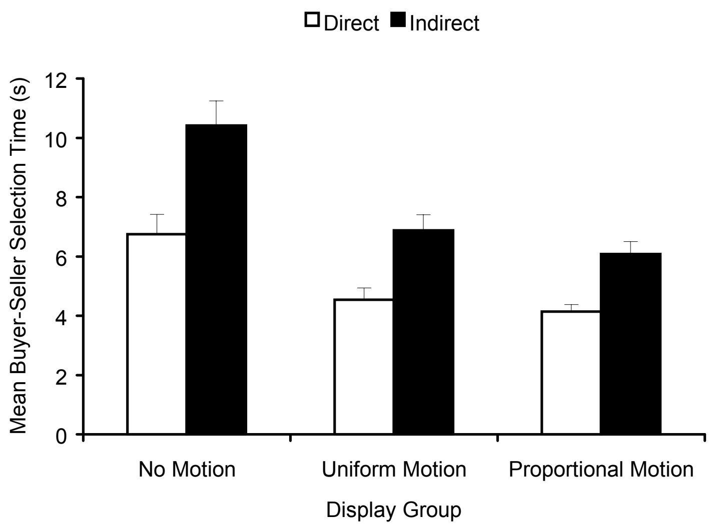


Figure 6. Mean buyer-seller selection times expanded across connection type as a function of display group. Error bars represent standard error.

Table 1

Descriptive statistics for time to complete the buyer-seller selection task by display group expanded across connection type.

	No Motion		Uniform Motion		Proportional Motion	
Connection Type	*M*	*SD*	*M*	*SD*	*M*	*SD*
Direct	6.75	2.77	4.53	1.66	4.14	0.98
Indirect	10.42	3.44	6.88	2.15	6.08	1.72

Note. All values are in seconds.

Table 2

Between-subjects t *tests of time to complete the buyer-seller selection task by connection type.*

	No Mtn - Uniform		No Mtn - Proportional		Uniform - Proportional	
Connection Type	$t(31)$	p	$t(30)$	p	$t(31)$	p
Direct	2.81*	.009	3.55*	.001	0.82	.417
Indirect	3.56*	.001	4.51*	< .001	1.18	.249

*$p < .05$

Table 3

Within-subjects t *tests of time to complete the buyer-seller selection task by display group.*

	No Motion		Uniform Motion		Proportional Motion	
	$t(15)$	p	$t(16)$	p	$t(15)$	p
Direct - Indirect	-6.47*	< .001	-8.49*	< .001	-6.22*	< .001

*$p < .05$

In addition, we measured the time required to select the path between the buyer and seller in indirect trials and counted the number of nodes in each path, but did not find significant differences among the display groups for either measure, $F(2, 46) = 0.240$, $p = .788$, and $F(2, 46) = 0.337$, $p = .716$, respectively.

Error Rate

Figure 7 shows the mean number of errors per trial—incorrect nodes selected as either buyer or seller—as functions of display group and connection type. A 3 (Display Group) x 2 (Connection Type) ANOVA found a significant main effect of display group, $F(2, 46) = 5.66$, $p = .006$. The motion advantage for error rate is illustrated in Figure 7a by the higher mean number of errors in the no-motion group ($M = 1.00$, $SD = 1.02$) than in the uniform-motion ($M = 0.429$, $SD = 0.520$) and proportional-motion ($M = 0.251$, $SD = 0.253$) groups. *T* tests indicated significant differences between the no-motion and uniform-motion groups, $t(31) = 2.05$, $p = .049$, and between the no-motion and proportional-motion groups, $t(30) = 2.78$, $p = .009$, but the difference between the uniform-motion and proportional-motion groups was not significant, $t(31) = 1.14$, $p = .265$. There was also a significant main effect of connection type, $F(1, 46) = 28.8$, $p < .001$, revealing a proximity effect for error rate. The error rate was lower in direct connection trials ($M = 0.182$, $SD = 0.363$) than in indirect connection trials ($M = 0.727$, $SD = 0.934$).

Figure 8 shows error rate expanded across connection type as a function of display group. The ANOVA results indicated a marginally significant interaction between display group and connection type, $F(2, 46) = 2.74$, $p = .075$, revealing an enhancement of the motion advantage in indirect connection trials. Tables 4, 5, and 6 show the descriptive statistics and results of the between-subjects and within-subjects *t* tests for the interaction. For both direct and indirect connection trials, the difference between the no-motion and the uniform-motion groups was at least marginally significant, whereas the difference between the uniform-motion and propotional-motion groups was not significant.

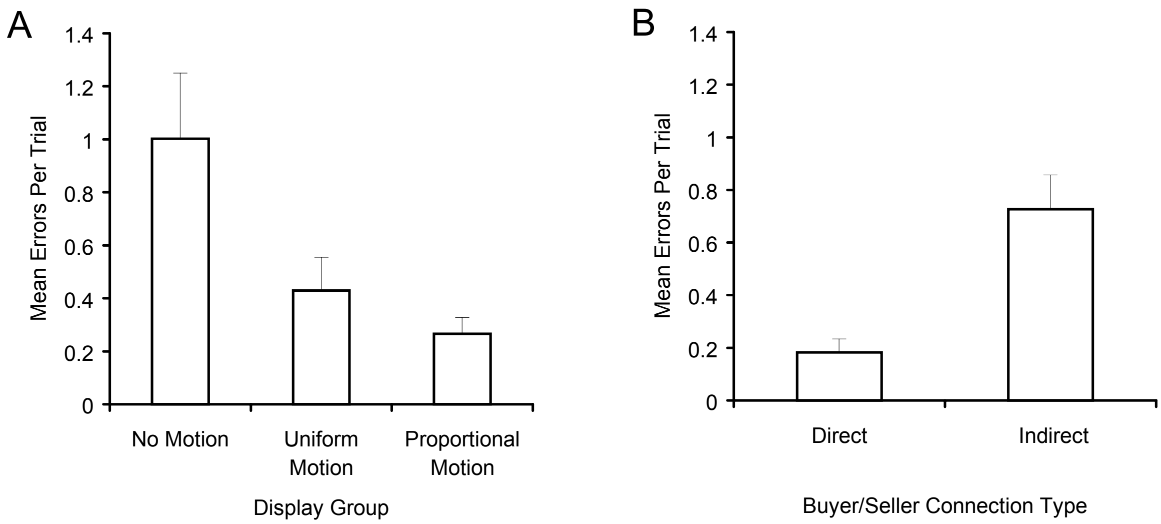


Figure 7. Main effects of (a) display group and (b) connection type on error rate, the motion advantage and proximity benefit, respectively. Error bars represent standard error.

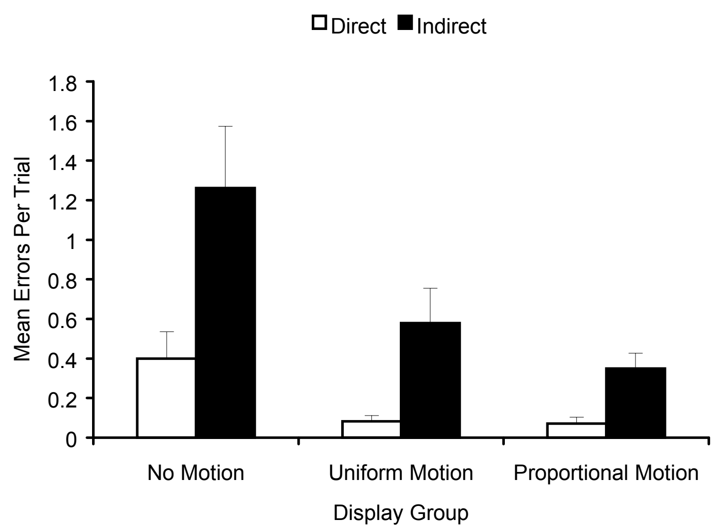


Figure 8. Error rate expanded across connection type as a function of display group. Error bars represent standard error.

Table 4

Descriptive statistics for error rate by display group expanded across connection type.

	No Motion		Uniform Motion		Proportional Motion	
Connection Type	*M*	*SD*	*M*	*SD*	*M*	*SD*
Direct	0.40	0.56	0.08	0.12	0.07	0.13
Indirect	1.26	1.28	0.58	0.73	0.35	0.32

Note. All values are number of errors per trial.

Table 5

Between-subjects t *tests of error rate by connection type.*

	No – Uniform		No - Proportional		Uniform - Proportional	
Connection Type	$t(31)$	p	$t(30)$	p	$t(31)$	p
Direct	2.29*	.029	2.29*	.029	0.26	.794
Indirect	1.90	.067	2.75*	.010	1.15	.258

$^*p < .05$

Table 6

Within-subjects t *tests of error rate by display group.*

	No Motion		Uniform Motion		Proportional Motion	
	$t(15)$	p	$t(16)$	p	$t(15)$	p
Direct - Indirect	-3.52*	.003	-2.90*	.010	-4.48*	<.001

$^*p < .05$

Order of Buyer-Seller Selection

The proportions of trials in which the buyer or seller was selected before the other as a function of display group are shown in Figure 9. For all display groups combined, the seller was selected first in a significant proportion of trials, $t(48) = 2.70$, $p = .010$, $M = 0.565$, $SD = 0.168$. For individual display groups, the proportion of trials in which the seller was selected first was significantly greater than chance only for the no-motion group, $t(15) = 2.64$, $p = .019$, $M = 0.558$, $SD = 0.0881$, and the proportional-motion group, $t(15) = 2.73$, $p = .016$, $M = 0.615$, $SD = 0.168$, though the trend was in favor of selecting the seller first in the uniform-motion group as well, $t(16) = 0.460$, $p = .652$, $M = 0.524$, $SD = 0.216$. Differences among the display groups were not significant, $F(2, 46) = 1.23$, $p = .301$.

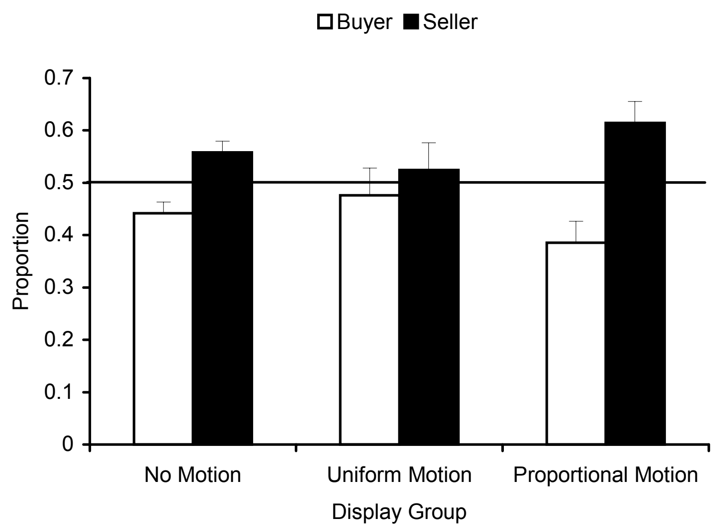
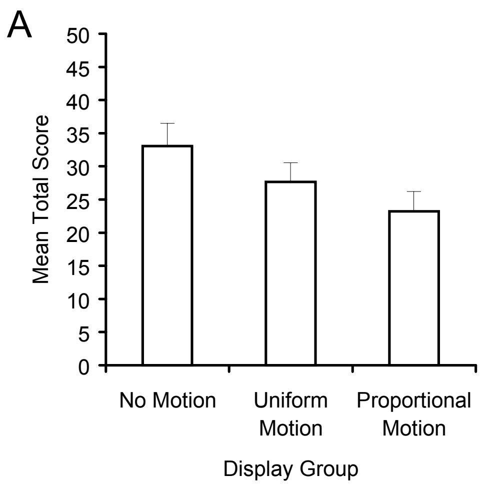


Figure 9. Proportions of trials in which the buyer or seller was selected first by display group. Error bars represent standard error.

Workload

Participants reported mental workload with the NASA-TLX by separately rating mental demand, physical demand, temporal demand, performance, effort, and frustration level on a scale from 0 to 100. The participants circled one of 21 tick marks on each of six Likert scales corresponding to each TLX dimension, each tick mark representing an increment of 5 points.

The results of the NASA-TLX are shown in Figure 10. A 3 (Display Group) x 6 (TLX Dimension: mental demand, physical demand, temporal demand, performance, effort, frustration level) ANOVA indicated a marginally significant main effect of display group, $F(2, 46) = 2.39$, $p = .103$, and a significant main effect of TLX dimension, $F(5, 230) = 22.0$, $p < .001$, though the interaction between display group and TLX dimension was not significant, $F(10, 230) = 0.423$, $p = .935$. The mean overall workload rating was highest for the no-motion display group ($M = 33.1$, $SD = 14.1$), followed by the uniform-motion group ($M = 27.6$, $SD = 11.9$), and the rating was lowest for the proportional-motion group ($M = 23.2$, $SD = 12.2$). Only the difference between the no-motion and proportional-motion display groups was significant, $t(30) = 2.12$, $p = .043$. The descriptive statistics and *t*-test results for the six TLX dimension scores are shown in Tables 7 and 8, respectively. Mental demand and temporal demand were the most significant contributors to overall workload.



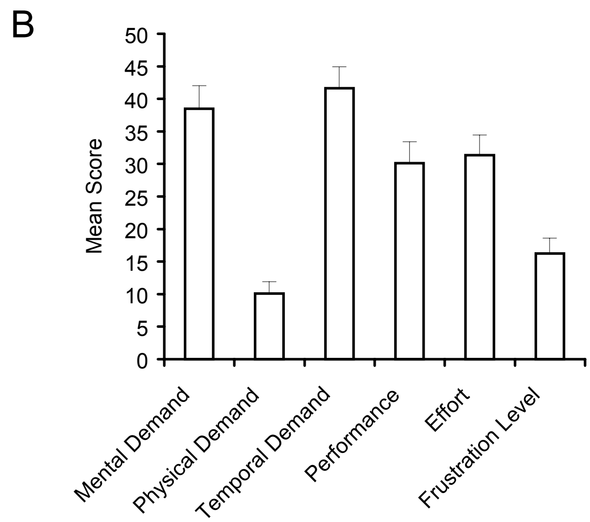


Figure 10. NASA-TLX workload scores as functions of (a) display group and (b) TLX dimension. Error bars represent standard error.

Table 7

Descriptive statistics for NASA-TLX dimension scores.

TLX Dimension	*M*	*SD*
Mental Demand	38.5	25.4
Physical Demand	10.1	12.8
Temporal Demand	41.6	23.6
Performance	30.1	23.8
Effort	31.3	22.2
Frustration Level	16.2	16.9

Table 8

Results of t tests between each pair of NASA-TLX dimension scores.

	Physical Demand		Temporal Demand		Performance		Effort		Frustration Level	
TLX Dimension	$t(48)$	p	$t(48)$	p	$t(48)$	p	$t(48)$	p	$t(48)$	p
Mental Demand	7.49*	< .001	-0.75	.458	1.82	.076	2.51*	.016	5.93*	< .001
Physical Demand			-8.77*	< .001	-5.36*	< .001	-6.78*	< .001	-2.34*	.024
Temporal Demand					2.30*	.026	2.53*	.015	8.05*	< .001
Performance							-0.35	.731	4.04*	< .001
Effort									4.75*	< .001

*$p < .05$

DISCUSSION

Overview of Results

The results show a clear advantage for the motion displays in the buyer-seller selection task. The time for participants to select the buyer and seller was significantly faster with moving arrows than with stationary arrows, and the response time advantage for the moving arrow displays increased when search difficulty, the separation between the buyer and seller, increased. Participants also made fewer errors with the motion displays, and error rates followed the same pattern as buyer-seller selection time, with a greater advantage for participants' use of the motion displays as search difficulty increased, eliminating the possibility of a speed-accuracy tradeoff. Participants also had lower subjective ratings of mental workload with the proportional-motion display than with the no-motion display, with the uniform-motion display falling between the two. Though there were no significant advantages for the proportional-motion display over the uniform-motion display, the data show trends that favor the proportional-motion display.

The unstructured nature of the path selection task may be the primary reason for the lack of significant differences among the displays for that task. Participants were instructed to choose any path, rather than choose an optimum path, making the task simple. We might have seen effects had the correct path been more difficult to determine and dependent on finding a pattern in PTDF magnitude and direction of flow, which the motion information would have directly supported.

Participants chose the seller first significantly more often than the buyer with the no-motion and proportional-motion displays but did not show such a marked preference with the uniform-motion display. That this preference was present with the no-motion display suggests that the participants may have consciously looked for the seller first but happened to see and select the buyer while searching for the seller on some trials. It is unclear why this preference effect was significant with the no-motion and proportional-motion displays but not with the uniform-motion display. A possible explanation is that the emergent features of expansion and contraction surrounding the seller and buyer in each trial were most salient in the uniform-motion display, in which motion was most coherent, so that even though participants may have preferred to search for the seller first, the buyer may have popped out during search for the seller more frequently than participants happened to see it in the no-motion display and more frequently than it popped out with the less-coherent contracting motion in the proportional-motion display.

Motion in Mimic Displays

There are a number of possible reasons why motion supported search and selection of buyers and sellers better than in the stationary arrow display. The salience of motion may have helped the participants attend to the parts of the display most relevant to the buyer-seller selection task, since larger moving items and faster-moving items are easy to find in a display (Hohnsbein & Mateef, 1992; Ivry & Cohen, 1992; von Mühlenen & Müller, 2000; Ware et al., 1992). The larger—and faster, in the case of the proportional-motion display—arrows tended to be located near and flowed between the buyer and seller in both motion displays, perhaps leading the participant's attention from the seller to the buyer. This may be why we saw an advantage for motion in the monitoring task, whereas Wiegmann et al. (2002) did not. In Wiegmann et al., the fastest-moving arrows were not necessarily associated with the search target. In addition, in their experiment, participants viewed a normally-operating system for a few seconds in each trial before a fault occurred. When the fault occurred, arrow movement speeds throughout the display could change, since faults could affect power flow throughout the network. This may have distracted from search for the worst violation (Olivers et al., 1999; Watson & Humphreys, 1998). Motion did not hinder performance with respect to the no-motion display because it directly supported the search task without causing a significant distraction in non-target areas of the display for either the search or path selection tasks. 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), accounting for the lack of a significant advantage in the search task over the uniform-motion display.

The motion of the arrows associated with the buyer and the seller also simplified search by creating an emergent feature (Wickens & Hollands, 2000, pp. 89, 98). The arrows were configured uniquely for the buyer and seller, since they were the only nodes in the displays where all arrows flowed either in or out. Motion probably 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; McLeod et al., 1991; Uttal et al., 2000; Valdes-Sosa et al., 1998). This explanation seems most likely to be the biggest contributor to the advantages we saw for motion, since it was present in both motion displays and because we didn't see significant differences between the two motion displays. The incoherence of the motion in the proportional-motion display may also have weakened the perception of common fate with respect to that in the uniform-motion display, further weakening the advantage of faster motion drawing attention to the buyer and seller.

Motion may also have aided the participants' understanding of the behavior of the power network. Enhancement of mental models might improve users' performance in a task such as the path selection task in helping them detect power flow patterns with less mental conversion than required with the no-motion display, as seen by Park and Gittelman (1995). Therefore, the enhancement of mental models might contribute to a performance advantage for the motion displays over the no-motion display, and perhaps an advantage for the proportional-motion display over the uniform-motion display in a more cognitively demanding path selection task, as mentioned above.

Implications for Display Design

Motion can be used successfully in mimic displays to aid understanding of the behavior of systems and aid search if the display is configured so that motion provides information that is directly relevant to the user's tasks and draws the user's attention to the areas most relevant to the current task. Task-relevant areas of displays can be highlighted with higher-speed motion or moving elements that configure themselves into moving patterns that are easily grouped together and separated from the rest of the display, such as expansion, contraction, rotation, and deformation (Ahlström & Börjesson, 1999; Meese & Harris, 2001). However, our results do not show a clear advantage for encoding flow magnitude with motion speed, suggesting that care should be taken to ensure that the resulting incoherence of the motion will not overpower the advantage of highlighting with faster motion and will not weaken emergent features defined by common fate. In addition, there may be no advantage to incorporating motion in displays to support tasks requiring integration of information when the integration task is simple, as we saw in the path selection task. When search tasks are difficult and time is critical, though, our results indicate that displays designed such that motion creates emergent features can improve performance significantly over displays without motion.

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APPENDIX A PARTICIPANT CONSENT FORM

Power Systems Visualization Experiment

You are being asked to participate in a study that investigates how the presentation of power systems information affects problem solving and decision-making. Your participation in this experiment will last approximately 1 hour, and you will be compensated for your involvement at the rate of $12.00 per hour.

Although there are no known risks involved in this experiment, you are free to discontinue participation at any point during the experiment with no loss in payment for the time invested up to that point. All information obtained through this experiment will be kept confidential. A code number will be assigned to the information you provide to ensure anonymity.

There are three phases of this experiment in which you will be asked to participate.

Phase 1: Pre-Trial
The experimenter will review this consent form with you, answering any questions or concerns that may arise. If you sign and agree to continue, you will be asked to provide certain demographic information such as age, sex, decision-making style, and problem solving strategies.

Phase 2: Trials
You will interact with a simple computer program to complete this phase. You will be presented with representations of power system networks. After a given time, a problem with the network will occur. Your task is to determine the nature of the problem and how to solve it. You will be asked to perform several such evaluations. The test will be self-paced, so you may pause periodically between trials if needed.

Phase 3: Post-Trial
A short questionnaire will be presented that asks for your impressions of the task and strategies in solving the problems. A short debriefing will take place when the questionnaire is completed, explaining the purpose and long-term benefits of the experiment.

There are no immediate benefits from participating in this study, but you will be helping to provide information that may help system designers provide better support for you, the user, in the future.

Statement of Consent

I acknowledge that my participation in this experiment is voluntary, and that I may withdraw at any time without loss of compensation for the time involved. I will receive the $12.00 per hour compensation fee upon completion of the experiment or withdrawal, and have received a copy of this form.

UNIVERSITY OF ILLINOIS
APPROVED CONSENT
FORM VALID UNTIL
8/14/2002

Participant: ______________________________ Date: ___/___/___

Investigator: ____________________________ Date: ___/___/___

The researcher in charge of this study is Dr. Douglas Wiegmann of the Institute of Aviation of the University of Illinois. If you have any questions about this study, please contact Dr. Wiegmann at (217) 244-8637. If you have questions about subject rights, please contact the Institutional Review Board at (217) 333-2670.

APPENDIX B PARTICIPANT ENTRANCE QUESTIONNAIRE

Entrance Questionnaire

1. Status (circle one) Undergrad Grad Faculty Staff N/A
2. If Undergrad, please circle year. Freshman Sophomore Junior Senior Senior+
3. Department / Major ___________________________________
4. Date of Birth (MM/DD/YY) ______/______/______ 5. Age ___________
6. Sex (circle one) Male Female
7. Do you have any form of colorblindness? (circle one) Yes No
8. How many classes on Power Systems have you taken or are currently taking? ______
    a. Please list the names of the classes taken that dealt with Power Systems.

    ____

    ____
9. How confident are you about your knowledge in Power Systems? (Circle a number)

    1 2 3 4 5 6 7

Not confident at all *Very confident*

10. Circle your choice of how you generally prefer to have data presented to you:

    Table Format or Graphical Format
11. Do you consider yourself to be more of a spatial or verbal person?

    (circle one) Spatial Verbal
12. When solving a problem, do you need to come up with the “best” solution or do you need to find only an adequate solution?

    (circle one) Best Adequate
13. When solving a problem, do you consider yourself to be more intuitive or more empirical?

    (circle one) Intuitive Empirical

APPENDIX C EXPERIMENT INSTRUCTIONS FOR PARTICIPANTS

The following instructions were given to the participants before beginning the experiment and were identical for each display group, except for the paragraphs indicated as unique to each group.

Power System Visualization Experiment Instructions

Thank you for agreeing to participate in this experiment. During the experiment you will be interacting with a simulation of a high voltage electric power system using a computer display similar to that shown in Figure 1. The simulation depicted in Figure 1 roughly approximates the power grid in the eastern portion of the U.S. and Canada. In actuality, the electric power grid in the eastern portion of North America is completely interconnected – it is really one large electric circuit. The grid itself consists of thousands of individual generators, millions of individual loads, and many thousands of miles of transmission wires. But while the grid is one electric circuit, the wires and generators are themselves owned by a number of different companies -- the local utilities. For example, here in Champaign-Urbana the local utility is Illinois Power, while in Northern Illinois the local utility is ComEd. Figure 1 the light blue ovals provides a fictitious (but still somewhat accurate) representation of these different utilities. The lines (branches) joining the ovals represent equivalent transmission lines that approximate the impedance characteristics of the thousands of transmission lines in the actual grid.

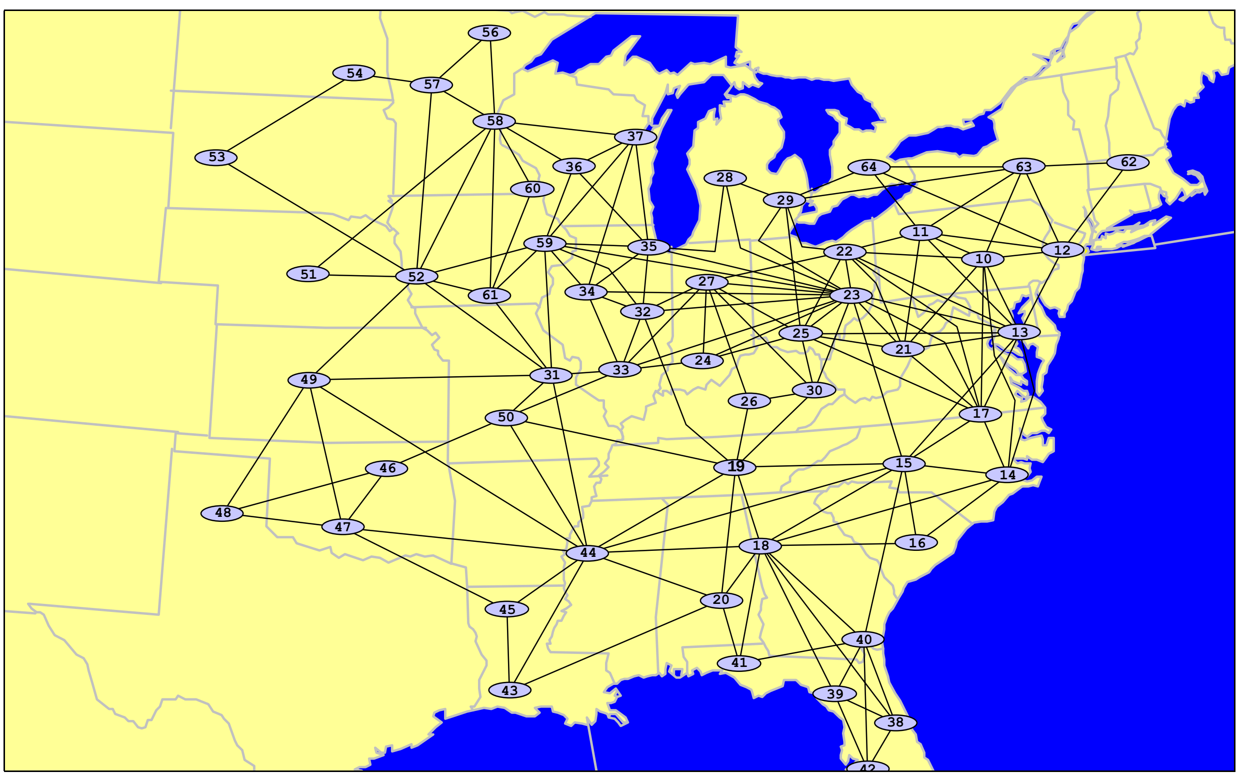

Figure 1: Experiment Diagram

One of the advantages for the utilities of sharing a common transmission system is that they can do power transactions. That is, they can buy and sell electric power. For example, if a utility in the southern portion of the U.S. needs additional power they can buy it from other utilities on the grid. The low impedance of the high voltage transmission system allows power to flow many hundreds of miles with relatively low losses. So it would not be unusual for a utility in the south to be buying power from utilities in Illinois or even further north.

These power transfers are accomplished by the seller increasing their generation and the buyer dropping theirs. There is then a net power transfer from the seller to the buyer. However, this power flow does not go along any particular path. Rather, it loops throughout a large portion of the network as dictated by the impedance of the actual transmission lines. This looping around of the power is known as "loop flow." How the power flows through the grid is calculated by the computer using values known as the PTDFs (power transfer distribution factors).

No-Motion Display Group: [During the experiment the PTDFs for different power transfers will be visualized on the display using magenta arrows as shown in Figure 2. The arrows will originate at the seller (oval 37 in this example) and terminate at the buyer (oval 32 in the example). The size of the arrow is proportional to the percentage of a power transaction between the seller and buyer that would flow on each branch. The arrow indicates the direction of the transfer (leaving the seller and going to the buyer). The seller will always be characterized by arrows all leaving, while the buyer will always be characterized by all arrows arriving. There will always be one seller and one buyer.]

Uniform-Motion Display Group: [During the experiment the PTDFs for different power transfers will be visualized on the display using magenta arrows as shown in Figure 2. The arrows will originate at the seller (oval 37 in this example) and terminate at the buyer (oval 32 in the example). The size of the arrow is proportional to the percentage of a power transaction between the seller and buyer that would flow on each branch. The arrow indicates the direction of the transfer (leaving the seller and going to the buyer). In addition, the display will be animated so the arrows will appear to be flowing at a uniform speed. The seller will always be characterized by arrows all leaving, while the buyer will always be characterized by all arrows arriving. There will always be one seller and one buyer.]

Proportional-Motion Display Group: [During the experiment the PTDFs for different power transfers will be visualized on the display using magenta arrows as shown in Figure 2. The arrows will originate at the seller (oval 37 in this example) and terminate at the buyer (oval 32 in the example). The size of the arrow is proportional to the percentage of a power transaction between the seller and buyer that would flow on each branch. The arrow indicates the direction of the transfer (leaving the seller and going to the buyer). In addition, the display will be animated so the arrows will appear to be flowing with the speed of the arrows proportional to the branch PTDF. The seller will always be characterized by arrows all leaving, while the buyer will always be characterized by all arrows arriving. There will always be one seller and one buyer.]

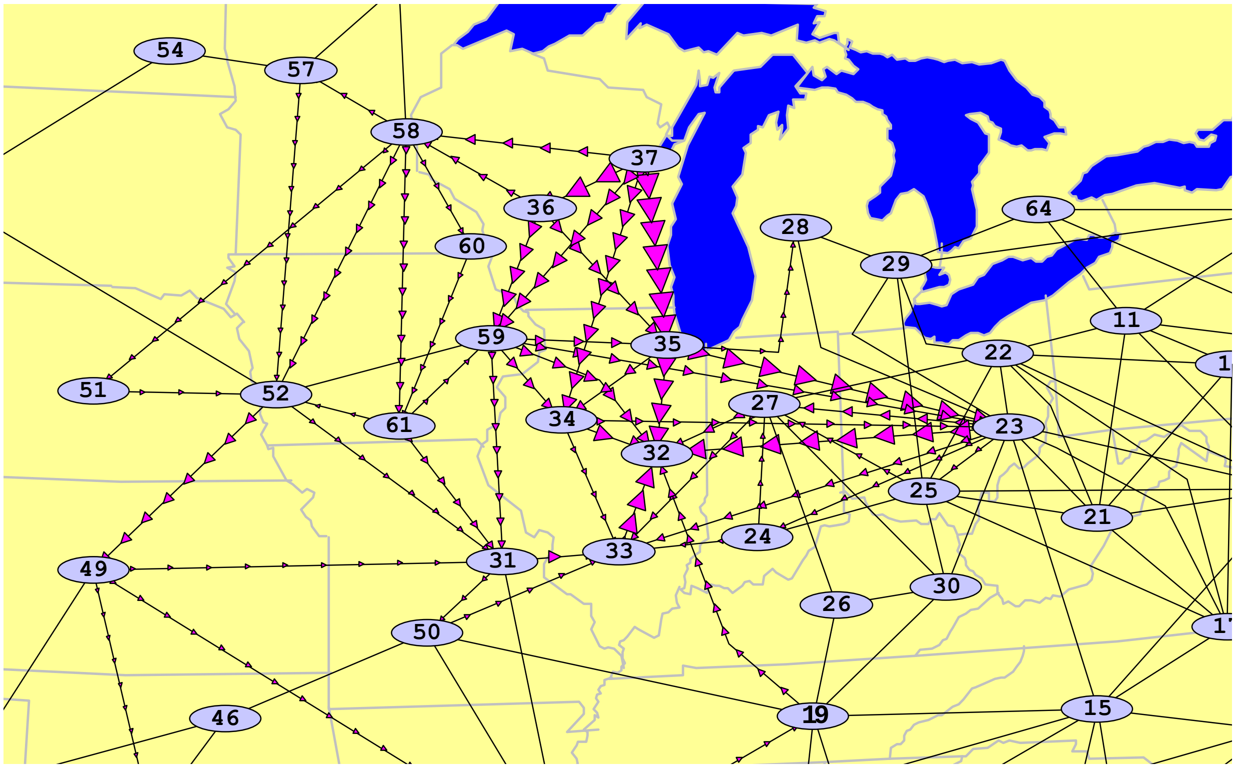

Figure 2: Example Power Transfer from Oval 37 to Oval 32

Since the arrow size is proportional to the PTDF value on each branch, the arrows provide a graphical view of loop flow. Ovals that participate in the loop flow will be characterized by some arrows entering and some arrows exiting (i.e., the power is just passing through this oval). In Figure 32 many ovals participate in the loop flow, including ovals 35, 36, 59, 23, 33, and many others. If the PTDF on a branch is sufficiently small no arrows are shown (for example, on the branch from 28 to 29). Because of this feature occasionally there may be ovals with small arrows just flowing in or just flowing out , such as oval 28. These ovals are not buyers and sellers; the small PTDFs in the opposite direction are simply too small for the arrows to show.

In the experiment you will participate in a series of trials. During each trial your job will be to determine, as quickly as possible, the seller and the buyer. Once you have done this, your job will be to determine what you view as the best path between the seller and the buyer, again as quickly as possible. A path is defined as a set of ovals interconnected by branches. Your path need not be the shortest and need not contain the fewest ovals. Use whatever criteria you like, but do it as quickly as possible. For example, in Figure 2 the seller is 37 and the buyer is 32. One path is 37-35-32. A alternative path is 37-59-34-32. Note also that ovals located in close proximity on the display may not be interconnected (for example 27 and 35).

The mechanics of each trial are as follows: At the beginning of each trial there will be no transaction present; the display will look similar to Figure 1. Then, after a variable time period of between 2 and 12 seconds a transaction will occur, indicated by arrows appearing on the display. Your first task is to left-click on the seller oval and buyer oval (in either order). When selected the seller oval will immediately turn green while the buyer oval will immediately turn red. You can not go to the next step until both the seller and the buyer have been selected. Next, click on other ovals to form a path joining the seller to the buyer. Once selected an oval on the path will turn white (these ovals can not be de-selected so don't worry if you want to change your path, just click on the new path). The trial will end when you have 1) selected the seller and buyer, and 2) selected a complete path between the seller and the buyer. Note, if the seller and buyer are directly interconnected the trial when immediately end after step 1. If you can not complete trial, the trial will eventually time out and prompt you to go on to the next trial.

During the experiment you will be participating in four practice trials and then 50 actual trials. The computer will automatically prompt you at the beginning of each trial, and let you know when the experiment is complete. Don't worry, the individual trials should go quite fast.

If you have any questions please ask the experimenter now. Thanks again for your participation in this experiment!!

APPENDIX D PARTICIPANT EXIT QUESTIONNAIRE

Exit Questionnaire

1. How well did the computer display show the direction of power flow in the network? (Circle a number)

1	2	3	4	5	6	7

Not well at all *Very well*

2. Did the displays ever appear to be cluttered or busy?

1	2	3	4	5	6	7

Never *Always*

3. Were the displays well organized from the user's point of view?

1	2	3	4	5	6	7

Never *Always*

4. Was the information depicted in the display easy to understand?

1	2	3	4	5	6	7

Never *Always*

Instructions: Carefully read the descriptions of the rating scales below. Then **circle** a mark on the rating sheet that corresponds to the level you experienced on each of the dimensions for the tasks you just finished performing.

Dimension	*Endpoints*	*Description*
Mental Demand	Low, High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	Low, High	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	Low, High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	Good, Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	Low, High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level	Low, High	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?