CRITIQUE AND RESPONSE

Why Fluid Dynamics Matters for Display Design in Process Control: Commentary on Bennett and Malek

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INTRODUCTION

As its name implies, *cognitive engineering* requires attention to the properties of both human cognition and engineering systems. Bennett and Malek (this issue) have done an exemplary job of investigating properties of human cognition that are pertinent to the design of animated mimic displays for process control systems. In so doing, however, they may have inadvertently overlooked some potentially vital properties of real engineering systems (e.g., how fluid flows in a piping network under normal and, especially, abnormal situations). A closer look at fluid mechanical factors reveals that using animation to depict flow rate will sometimes provide operators with misleading feedback that could negatively affect plant safety.

FLOW PATTERNS IN A PIPING NETWORK

Implications for Animated Mimic Displays

Bennett and Malek (this issue) motivated their research on animated mimic displays by the need to support fault management behavior. In their discussion the authors return to this issue, stating that "the inclusion of animation in mimic displays could ... improve the detection and diagnosis of faults" (p. 448). However, the two studies conducted evaluated performance on a quantitative psychophysical task, not a fault management task. It is not clear how results from an elemental task of quantitative judgments of velocity generalize to the more complex relational task of fault management. Therefore, it is of interest to consider the implications of using an animated mimic display in a complex piping network, typical of that found in real-world applications.

Although the usability of a design can only be assessed empirically, its usefulness can be evaluated analytically by identifying the control requirements associated with a problem (Rouse, 1990). In this case these requirements can be examined by reviewing how fluid flows in a piping network. We initially consider the simplest case (shown in Figure la) of fluid flowing through a pipe controlled by a valve (VA), resulting in a sensed flow rate (FA).

Breakdown of Normal Expectations about Flow Rate

Conservation of mass requires that the instantaneous flow rate of an incompressible fluid in a rigid pipe be the same at every location along a pipe segment. A pipe segment is defined as any continuous length of pipe uninterrupted by branch or feeder pipes. Clearly, flow rate will change across a branch or feeder point, as fluid will leave or enter the pipe at such a location. Under normal operating conditions, it is therefore appropriate to represent the flow in an entire pipe segment based on the output of a single flow sensor. A display of the type advocated by Bennett and Malek (this issue) would be effective in this case.

However, consider the more critical and demanding case of a pipe break or leak. Depending on the location and severity of the leak or break, the flow rate along the pipe could change drastically as a function of spatial location. For example, the flow rate downstream of the flow sensor location could be much less than that at the flow sensor itself because of the leaking fluid.

However, an animated mimic display like that shown in Figure 1b would erroneously suggest

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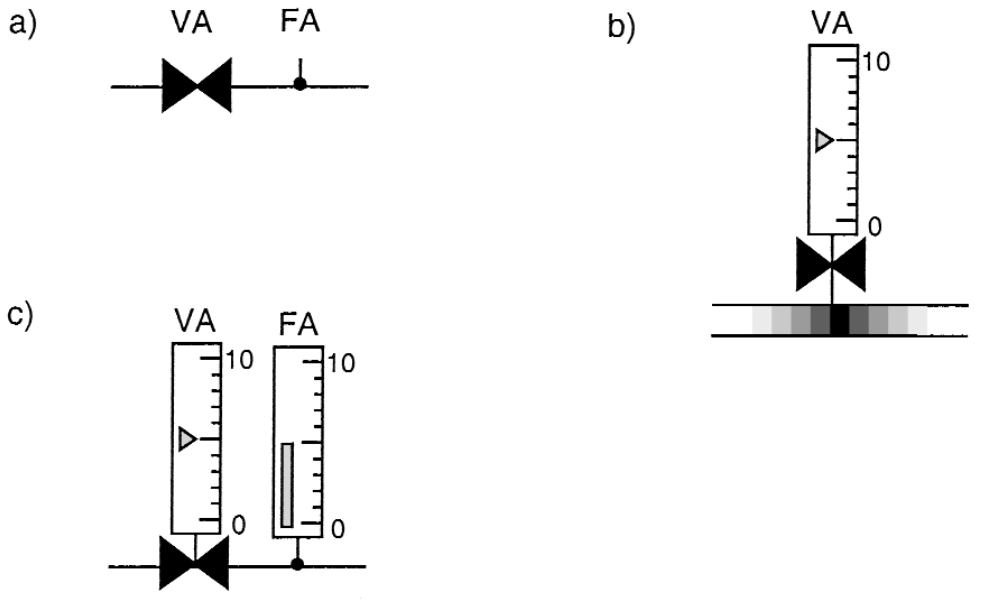

Figure 1. (a) A piping and instrumentation diagram for a valve and a flow sensor along a pipe segment; (b) an animated mimic display based on the technology advocated by Bennett and Malek (this issue); and (c) an alternative display that avoids the problems associated with the animated mimic display.

that fluid is flowing at the same flow rate all along the pipe segment. It would do so because the display extrapolates from the flow datum collected at a single location to create a very compelling and attention-grabbing animated representation of what is normally true (i.e., constant flow rate all along the pipe). This normal relationship is an inference because we do not have flow sensors all along the pipe. During some faults, this inference is incorrect, and the animated display may discourage operators from entertaining valid hypotheses about where the pipe break or leak might be.

The resulting situation is analogous to that observed in the Three Mile Island (TMI) control room (Rubinstein, 1979). In that case, a display showed that a valve was closed when it was actually stuck open because the display depicted what should have happened, not what was really happening. Similarly, the animated mimic display would indicate what the flow rate downstream of a break should be (in the absence of a break), not what it really is. As the TMI accident showed, such a misleading indication can contribute to a serious threat to plant safety.

Flow Rate Is Not Equal to Velocity

Although they did not collect any training data, Bennett and Malek also speculate that "the inclusion of animated mimic displays in computerized learning systems could improve the efficiency of training" (p. 448). The physics of fluid flow in pipe networks suggests that this may not always be so. Specifically, it is important to realize that velocity in a pipe segment is not the same as flow rate if the pipe diameter changes, such as typically happens in a reducing or expanding pipe section adjacent to a piece of equipment (e.g., velocity will increase in a reducing section).

Bennett and Malek use the terms flow rate and velocity interchangeably, sometimes referring to a "representation of flow rates" (p. 433) and other times referring to "the velocity of flow that is being depicted" (p. 439). In their display, these two variables appear to be the same because the velocity of the animation is used to depict the flow rate of the fluid. Such a mapping between display and environment would tend to encourage operators to conflate fluid velocity with flow rate, which would be incorrect in pipe segments of variable diameter. Thus rather than being "likely to facilitate the development of appropriate conceptual understandings (mental models) of complex systems" (p. 448), Bennett and Malek's animated mimic display is potentially more likely to induce dysfunctional mental models under certain conditions.

Again, the TMI accident serves as a good analog (Rubinstein, 1979). The TMI operators did not distinguish between pressurizer level and reactor coolant system inventory. These two variables are normally correlated, but during the TMI accident it was very important for operators to distinguish between them. The operators' failure to do so contributed to the accident. Similarly, it is likely that operators will not distinguish between fluid velocity and flow rate because the animated mimic display uses velocity to represent flow rate. In situations in which it is important to distinguish between these two variables, operators are very likely to run into trouble, particularly because the display animation is so compelling. As with TMI, this situation could contribute to seriously threatening plant safety.

Flow Rate at Junctions

Finally, we consider a more complex situation, in which feeders or branches are present. Take the case of a single large pipe branching into two smaller "daughter" pipes, each of which carries half the flow present in the large pipe. At this branching location, an animated mimic display of the type proposed by Bennett and Malek would show *fast-moving* fluid approaching the junction in the large pipe and *slow-moving* fluid leaving in the two daughter pipes. Would this display facilitate operator understanding? We are not convinced that it would; at the very least, empirical testing of the display for this configuration would be required before defensible claims about training efficiency could be made.

Are these problems relevant to display design or are they merely instrumentation design issues? We believe that these two types of problems should not be studied independently. The design of instrumentation should not be considered apart from display design because the availability and location of sensors can have important implications for human performance (Reising, 1999; Vicente, Christoffersen, & Hunter, 1996). If the requisite variables are not being sensed, performance will be limited, regardless of how well the display is designed. Conversely, the design of displays should not be considered apart from instrumentation design because the way in which the display represents the information obtained from sensors can also have important implications for human performance. If the sensor data are presented in a misleading fashion, then performance will also be limited, even if the sensors are properly designed and functioning normally. Thus display designers should consider instrumentation constraints when proposing a new display concept.

Are there any alternative display concepts that do not suffer from the problems outlined earlier? The interaction between sensor design and fault management performance is an unavoidable design challenge, but cognitive engineers can take steps to minimize the problems associated with animated mimic displays. One example is presented in Figure 1c. In this case, the flow rate is indicated at a single location on the pipe corresponding to the location of the flow sensor. In this design the potential for misleading the operator is reduced because no indication is given as to what the flow might be at other locations along the pipe. Rather than using a sensor datum at one location to infer what might be going on elsewhere, this design presents a sensor datum only at the place where it is being collected.

CONCLUSIONS

Cognitive engineering has the potential to make significant improvements to safety, productivity, and worker health in complex sociotechnical systems (Vicente, 1999). To recognize this potential, researchers must leverage insights about human cognition, as Bennett and Malek have done (this issue). However, researchers cannot ignore the environmental aspect of these systems. The design of effective displays cannot be based solely on psychological knowledge. For example, in process control, fluid dynamical and other engineering-based factors must also be taken into account(see Itoh, Sakuma, & Monta, 1995). Just as the way the visual system works puts important constraints on what counts as an effective display, so does the way in which fluid flows in a realistic pipe network. The latter constraints cannot be escaped because fluids keep on behaving the way they do, regardless of how displays are designed. This point generalizes well beyond the details of this example. If cognitive engineering is going to make its mark on applied problems in industry, then researchers will have to devote as much attention to engineering as to cognition (Vicente et al., 1996).

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