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Shaping Expertise Through Ecological Interface Design: Strategies, Metacognition, and Individual Differences

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SHAPING EXPERTISE THROUGH ECOLOGICAL INTERFACE DESIGN: STRATEGIES, METACOGNITION, AND INDIVIDUAL DIFFERENCES

by

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for the degree of Master of Arts
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Abstract

This thesis examined the effect of interface designs on participants' adaptation, focusing on the role of individual differences in process control. The experiment was conducted on DURESS II, an interactive thermal-hydraulic simulation with two interfaces: traditional (including only physical information) and ecological (including physical and functional information). The experiment was 6 months in duration and included a variety of conditions. A detailed analysis of a group of early and late start-up trials was conducted in order to investigate changes in expertise. A series of performance measures were developed as indicators of adaptation. Generally, participants effectively using the traditional interface, unlike those using the ecological interface, used mainly standardized procedures for operating the system. All participants made few metacognitive statements while thinking aloud during normal trials. Further, participants using the ecological interface exhibited better performance on both normal and fault trials if they scored higher in the holist cognitive style.

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Table of Contents

Abstract ii

Acknowledgements iii

List of Tables vi

List of Figures viii

1. Introduction and Literature Review **1**

1.1 Ecological Interface Design **1**
1.1.1 SRK Taxonomy 1
1.1.2 Abstraction Hierarchy 2
1.1.3 DURESS System 2

1.2 Individual Differences **6**
1.2.1 Mental Strategies 7
1.2.2 Metacognition 7
1.2.3 Cognitive Learning Styles 10

1.3 Aim **13**

1.4 Hypotheses **14**

2. Method **15**

2.1 Participants **15**

2.2 Materials **15**

2.3 Procedure **16**
2.3.1 Data Sources 17
2.3.2 Analysis Tools 18

3. Results **22**

3.1 Behavioral Evidence of Mental Strategies **22**
3.1.1 Action Transition Graphs 22
3.1.2 Clustering 29
3.1.3 State Space Diagrams 31
3.1.4 Mass and Energy Inventories 43
3.1.5 Timelines 58
3.1.6 Information Theory 63

3.2 Verbal Protocols **65**
3.2.1 Verbalizations 65
3.2.2 Strategies 68
3.2.3 Metacognition 73

3.3 Cognitive Learning Styles 77
3.3.1 Study Process Questionnaire 77
3.3.2 Spy Ring History Test 79

4. Discussion 83

4.1 The Effect of Experience on Strategies 83
4.1.1 Measures of Expertise 83
4.1.2 Evidence of Adaptation 84

4.2 The Effect of Interface on Strategies 85

4.3 The Role of Metacognition 87

4.4 The Role of Individual Differences 88

4.5 Implications 88

4.6 Limitations 89

4.7 Future Directions 90

5. References 92

6. Appendices 97

6.1 Appendix A - Instruments for Assessing Individual Differences 97
6.1.1 Test for Holism-Serialism 97
6.1.2 Test for Approaches to Learning 98

6.2 Appendix B - Trial Schedule 99

6.3 Appendix C - Verbal Protocols 101

List of Tables

Table 2.1. Summary of Participant Groupings 15
Table 3.1. Mean Action Transition Graph Complexity 25
Table 3.2. Steady State Times for Start-up 26
Table 3.3. Correlation Between Action Transition Graph Complexity and Steady State Time 26
Table 3.4. Difference From Optimal Mass Input Strategy 28
Table 3.5. Correlation Between Difference from Optimal Mass Input Strategy and Performance 29
Table 3.6. ARC Scores for Initial Block of Trials 30
Table 3.7. ARC Scores for Final Block of Trials 30
Table 3.8. Correlations Between Average Steady State Time and Average ARC Scores 31
Table 3.9. Mean Path Length for Reservoir 1 from State Space Diagrams 36
Table 3.10. Mean Path Length for Reservoir 2 from State Space Diagrams 37
Table 3.11. Mean Difference from Univariate Control Strategy for Final Block of Trials 38
Table 3.12. Correlations Between Path Length and Steady State Time 39
Table 3.13. Mean Area Under Distance to Goals versus Time Graphs for Reservoir 1 42
Table 3.14. Mean Area Under Distance to Goals versus Time Graphs for Reservoir 2 42
Table 3.15. Correlations Between Area Under Distance versus Time Graph and Steady State Time 43
Table 3.16. Area of Deviation from Temperature Goal Line for Reservoir 1 53
Table 3.17. Area of Deviation from Temperature Goal Line for Reservoir 2 53
Table 3.18. Correlations Between Area of Deviation from Goal Line and Steady State Time 54
Table 3.19. Final Mass Inventory for Reservoir 1 55
Table 3.20. Final Mass Inventory for Reservoir 2 55
Table 3.21. Correlation Between Final Mass Inventory and Steady State Time 56
Table 3.22. Chi Square for Reservoir 1 Volume, Trials 1-22 57
Table 3.23. Chi Square for Reservoir 2 Volume, Trials 1-22 57
Table 3.24. Chi Square for Reservoir 1 Volume, Trials 196-217 58
Table 3.25. Chi Square for Reservoir 2 Volume, Trials 196-217 58
Table 3.26. Percentage of Control Actions in First Quarter of Trial 59
Table 3.27. Percentage of Heater Control Actions in Final Three Quarters of Trial 62
Table 3.28. Number of Heater Control Actions in Trial 63
Table 3.29. Average Information in Final Block of Trials 65
Table 3.30. Individual Differences in Average Amount of Verbalization per Minute 66
Table 3.31. Number of References to a Valve Minimization Strategy 69
Table 3.32. Number of Steady State Heater Setting as a Ration of Reservoir Demand 70
Table 3.33. Number of References to Perceptual Features of the Interface 70

Table 3.34. Number of References to Standardized Operating Procedures 71
Table 3.35. Number of References to Precise Quantitative Values 72
Table 3.36. Number of References to Trial and Error Strategy 73
Table 3.37. Number of Statements Explaining or Justifying Control Actions 74
Table 3.38. Number of Metastrategic Phrases 75
Table 3.39. Number of Self-Monitoring Phrases 75
Table 3.40. Number of Predictions of End of Start-up 76
Table 3.41. Prediction Accuracy for Precise Quantitative Predictions 77
Table 3.42. Participants' Approaches to Learning 78
Table 3.43. Chi Square for Distribution of High Scores in SPQ 79
Table 3.44. Classifications from Spy Ring History Test 80
Table 3.45. Correlations Between Holism Scores and Performance 81
Table 6.1. Sample of SPQ Items 98

List of Figures

Figure 1.1 P Interface for DURESS II (Christoffersen et al., 1994b). 4

Figure 1.2 P+F Interface for DURESS II (Christoffersen et al., 1994b). 6

Figure 2.1 Example Action Transition Graph. 18

Figure 2.2 Example State Space Diagram. 20

Figure 3.1 Comparison of action transition graphs for first and last trial - P+F group. 23

Figure 3.2 Comparison of action transition graphs for first and last trial - P group. 24

Figure 3.3 Comparison of state space diagrams for first and last trial - P+F group reservoir 1. 32

Figure 3.4 Comparison of state space diagrams for first and last trial - P+F group reservoir 2. 33

Figure 3.5 Comparison of state space diagrams for first and last trial - P group reservoir 1. 34

Figure 3.6 Comparison of state space diagrams for first and last trial - P group reservoir 2. 35

Figure 3.7 Comparison of graphs of distance to goals versus time for first and last trial - P+F group. 40

Figure 3.8 Comparison of graphs of distance to goals versus time for first and last trial - P group. 41

Figure 3.9 Comparison of energy inventory vs. mass inventory graphs for first and last trial - P+F group reservoir 1. 44

Figure 3.10 Comparison of energy inventory vs. mass inventory graphs for first and last trial - P+F group reservoir 2. 45

Figure 3.11 Comparison of energy inventory vs. mass inventory graphs for first and last trial - P group reservoir 1. 46

Figure 3.12 Comparison of energy inventory vs. mass inventory graphs for first and last trial - P group reservoir 2. 47

Figure 3.13 Comparison of graphs of E/M vs. time for first and last trial - P+F group reservoir 1. 49

Figure 3.14 Comparison of graphs of E/M vs. time for first and last trial - P+F group reservoir 2. 50

Figure 3.15 Comparison of graphs of E/M vs. time for first and last trial - P group reservoir 1. 51

Figure 3.16 Comparison of graphs of E/M vs. time for first and last trial - P group reservoir 2. 52

Figure 3.17 Comparison of time lines for first and last trial - P+F group. 60

Figure 3.18 Comparison of time lines for first and last trial - P group. 61

Figure 3.19 Amount of verbalization per minute versus trial number for P+F group and P group. 67

1. INTRODUCTION AND LITERATURE REVIEW

Computerization is influencing many sectors of the work force, changing both the work environment and the cognitive demands placed on the workers. Computers can support and expand human cognitive activities, yet "the capacity to do more amplifies the potential magnitude of both our successes and our failures" (Woods & Roth, 1988, p. 416). In the nuclear industry for example, the consequences of failure are particularly dramatic, and thus the design of control room automation must be considered carefully (Vicente, 1990a).

Computer interface designs must take into account the constraints of the work environment, the specific tasks, and the cognitive processes of the human user (Norman, 1986; Woods & Roth, 1988; Rasmussen, 1988). In this way, the interface can help to bridge the gap between the physical system and the psychological goals of the user. The interface should support human problem solving by helping the user to manage system complexity and by providing an accurate reflection of the work environment. Ecological Interface Design (EID) provides a theoretical framework for interface design in complex work environments that addresses these concerns. This thesis evaluates the influence of interface type, both ecological and traditional, on the participants' performance and cognition.

1.1 Ecological Interface Design

EID derives its name from its links to ecological psychology (Gibson, 1982). In EID, as in ecological psychology, the behavior of the human-machine system is understood within the context of the specific work environment (Vicente, 1990b). Rasmussen's skill-rule-knowledge (SRK) taxonomy and abstraction (or means-end) hierarchy provide the conceptual foundation of EID (Vicente & Rasmussen, 1992).

1.1.1 SRK Taxonomy

According to the SRK taxonomy, there are three levels of cognitive control: skill based behavior, rule based behavior, and knowledge based behavior (Rasmussen, 1983). Skill based behavior and rule based behavior are predominantly perceptual-motor while knowledge based behavior is analytical. Ecological interfaces should support all three levels of processing. Perceptual-motor processing is faster and less resource demanding, but analytical processing allows users to cope with novelty. To promote automated behavior (skill based behavior), the user should be allowed to act directly on the interface (usually via a mouse). To activate goal-directed mental subroutines (rule based behavior), there should be a consistent one-to-one mapping between cues on the interface and constraints in the work environment. To support conscious reasoning and testing of plans (knowledge based behavior), the work domain should be represented as an abstraction hierarchy.

1.1.2 Abstraction Hierarchy

Interfaces designed according to an abstraction hierarchy provide models of the system at different levels of detail and abstraction. The abstraction hierarchy supports problem solving by explicitly representing goal-relevant constraints describing the structure of the system. Any abnormalities are identified as broken constraints; this is particularly useful for coping with unfamiliar, unanticipated situations. The operators can move between the higher, abstract (functional) representations and the lower, concrete (physical) representations of the system while monitoring the system state or diagnosing problems. Moving upwards through the abstraction hierarchy will provide the reasons for a situation -- the 'why' -- and moving downwards will provide the physical causes -- the 'how' (Rasmussen, 1985; 1986). A traditional interface does not provide this type of underlying cognitive support. Several studies show that problem solving protocols in different domains also can be mapped onto an abstraction hierarchy (Duncker, 1945; de Groot, 1965).

The DURESS simulation provides both an interface designed according to the principles of EID, and a traditional interface. (For a detailed discussion of the application of the abstraction hierarchy framework to DURESS II, see Bisantz & Vicente, 1994). In this thesis, DURESS II is used as the experimental setting for evaluating the interaction between interface type, and the participants' control behavior and cognition.

1.1.3 DURESS System

DURESS (DUal REservoir System Simulation) is a thermal-hydraulic process control simulation (see Figure 1.1). It is a highly-simplified, yet representative, real-time computer model (Vicente, 1995; Vicente & Rasmussen, 1990). DURESS II was designed to exhibit some of the characteristics of a complex system. The variables are coupled, so that one control action may effect several different parts of the system. The variables also have time lags such that the consequences of manipulating a control are not immediately obvious to the novice. In addition, there is some degree of risk involved since ineffective control may cause the system to fail (or blow-up).

In DURESS II, users may control the system by adjusting the settings of the heaters, pumps, and valves. The goal is to satisfy the required output water-flow rates (demands) and temperatures for each of two reservoirs, and to keep the system within tolerance of these values (steady state) for five consecutive minutes. The temperature goals for each reservoir remain the same for each trial (40°C and 20°C), while the demand pairs vary between trials.

There are two redundant feedwater streams which each contain one pump and three valves (pump, PA, and valves, VA, VA1 and VA2 for feedwater stream A; and pump, PB, and valves, VB, VB1, and VB2 for feedwater stream B). The participants may use any or all of these pumps and valves to meet the external demands for water. There is also one valve that controls the output flow from each reservoir (VO1 and VO2 for reservoirs 1 and 2 respectively). Water enters the system at a temperature of 10°C, and is heated to the required temperatures using the heaters in each reservoir (HTR1 and HTR2).

There are two different interfaces for this system. The traditional interface gives only physical information about the system (P interface) while the ecological interface gives both physical and functional information about the system (P+F interface). The P interface, illustrated in Figure 1.1, provides a physical representation of the system. It indicates the positions and settings of each component, and the required output values. This interface is typical of traditional computer-based interface designs for process control systems, and serves as an experimental control condition.

The first item on the left of the P interface is a thermometer which indicates the input water temperature. Immediately to after the thermometer, the flow splits into two feedwater streams which flow to two pumps. The pumps may be switched on and off by clicking on them using a mouse. Next in sequence are the primary valves (VA and VB). These valves may be set by clicking on a setting between 0 and 10, or by dragging the triangular indicator to the appropriate position. The feedwater streams split again after the primary valves, leading to secondary valves (VA1, VA2, VB1, and VB2). These valves operate identically to the primary valves.

Next the water arrives at two reservoirs. The level of water in the reservoirs is indicated by a shaded region, ranging up to a maximum of 100 units. The heaters are located below the reservoirs, and have a range of 0 to 10 units. The output valves, to the right of the reservoirs, can be set between 0 and 20 units. The demand goal region is indicated by a bar on the output valve scale. Both heaters and output valves can be set by either clicking or dragging the indicator to the desired setting. Finally, the temperature of the water in the reservoirs is displayed on the thermometers next to the reservoirs. The goal temperature goal regions are indicated by a bar on each of the thermometers.

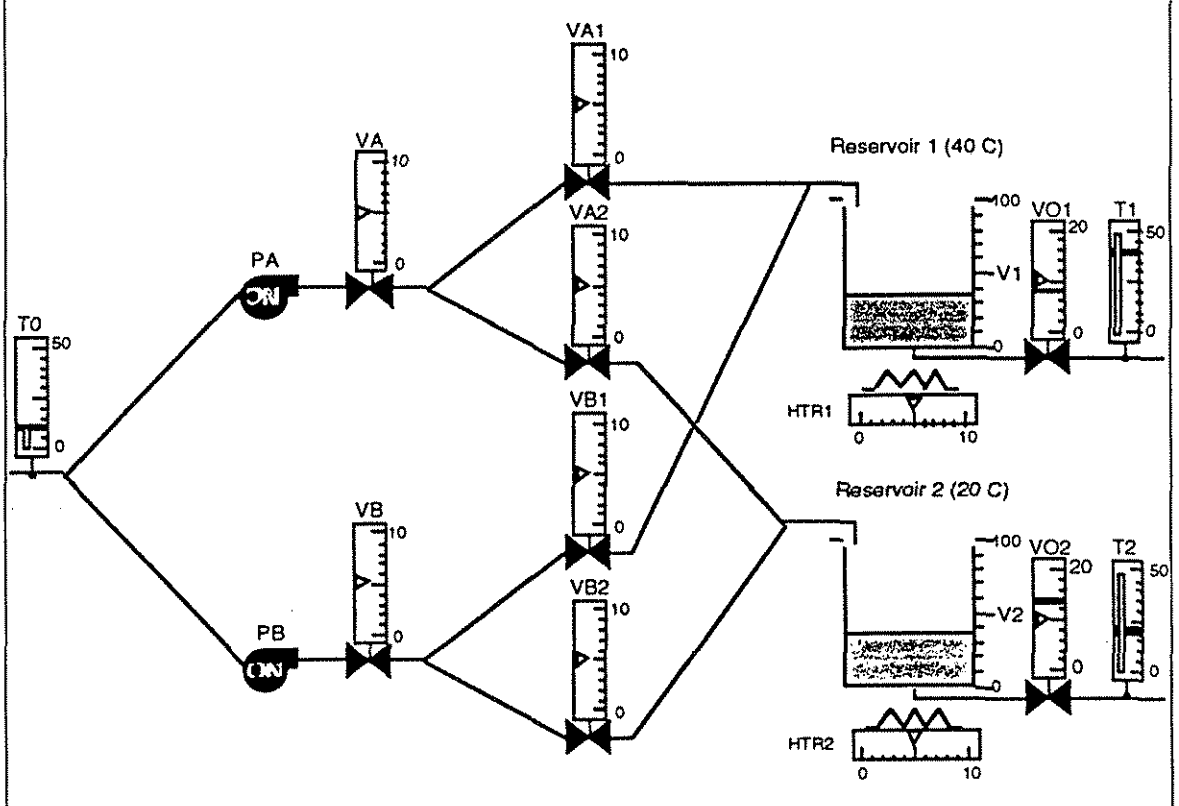

Figure 1.1 *P Interface for DURESS II (Christoffersen et al., 1994b).*

The P+F interface, illustrated in Figure 1.2, was designed according to the principles of EID (Vicente & Rasmussen, 1990). This interface contains physical information about the components, as in the P interface. Also, all of the components operate as in the P interface. In addition, the P+F interface indicates higher-order functional relationships within the system based on an abstraction hierarchy analysis. This additional information is intended to provide cognitive support for problem solving (knowledge based behavior).

Each valve has a flow meter placed beside it with the same range as the associated valve. Also the reservoirs in the P interface have been replaced by a box containing representations of the mass and energy balances (the rectangular graphics on the left and right respectively). Both of these graphics operate similarly. The inputs are shown at the top, the inventories are measured along the side, and the outputs, are shown at the bottom of the graphics. The slope of the line joining the input and output indicates the rate at which the mass (or energy) inventory should be changing. For example in Figure 1.2, the mass input is less than the mass output for each reservoirs, so the volumes should be decreasing. When the line is vertical, the volume (or energy) should not be changing. The graphic between the mass and energy balances shows the relationship between mass, energy, and temperature. (For a more detailed description of the interfaces, refer to Christoffersen, Hunter, & Vicente, 1994b).

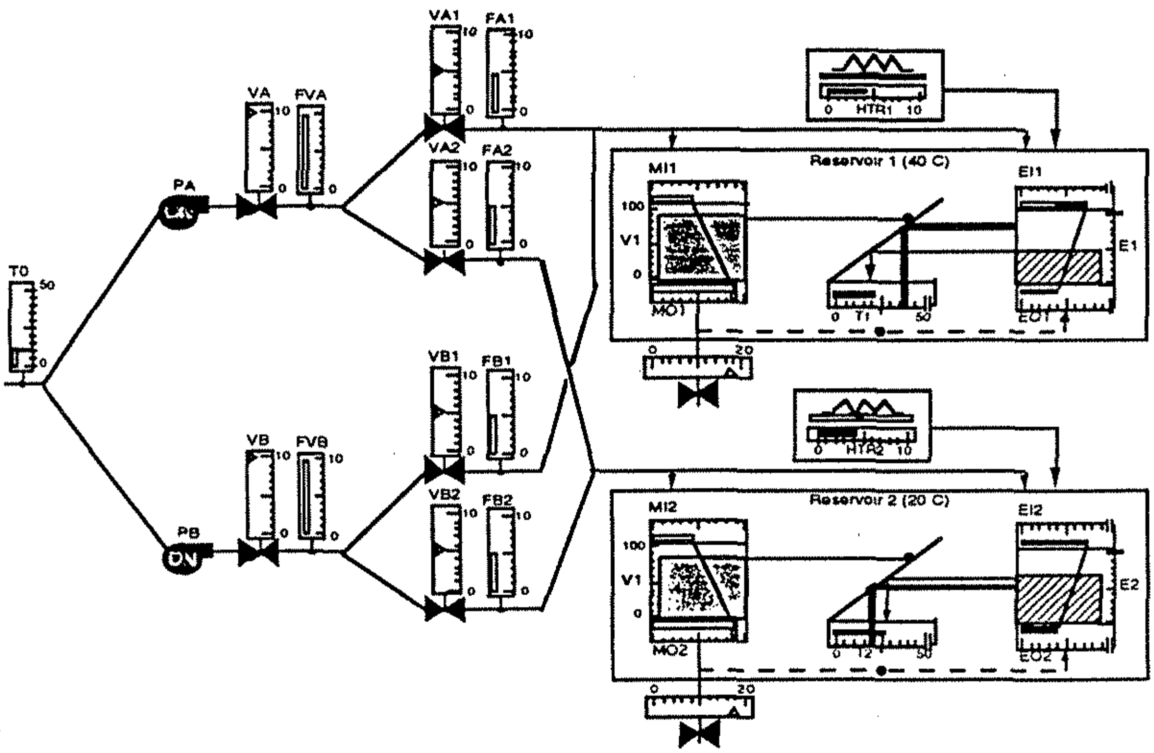

Figure 1.2 *P+F Interface for DURESS II (Christoffersen et al., 1994b).*

1.2 Individual Differences

Unfortunately, ecological interfaces do not seem to support all users equally; individual differences can influence the performance benefits that users gain from the P+F interface, as well as their preferences (Christoffersen, Hunter, & Vicente, 1994b; Meshkati, Buller, & Azadeh, 1994). There is also a relationship between individual differences and fault diagnosis performance (Meshkati, et al., 1994; Morris, & Rouse, 1985; Rouse, & Rouse, 1982). Individual differences can have implications for the selection and training of operators (Pask & Scott, 1972; Moore, Smith, & Telfer, 1994). Further, interface designs may be compared more directly by taking individual differences into account. The differences between users will contribute to the error variance unless personality factors are considered explicitly.

This thesis will examine three indications of individual differences: mental strategies, metacognition, and cognitive learning styles. In particular, the interaction between individual differences and interface type will be evaluated.

1.2.1 Mental Strategies

When individuals use the DURESS II simulation, their behavior is constrained to some extent both by the work domain (as described by the abstraction hierarchy) and the control tasks (e.g., bring the system from a shut-down state to steady state). Within these constraints, the way in which users accomplish control tasks can vary. Mental strategies are a set of procedures for carrying out a task[1]. These strategies are based on the users' mental model of the system, their interpretation of information using this mental model, and various tactical rules (Rasmussen, 1981; Rasmussen & Jensen, 1974). Thus, mental strategies provide one window on users' mental model of the system within the context of a specific situation, their levels of expertise, and their preferences.

A cognitive work analysis of the DURESS II system has identified effective mental strategies that individuals can use to reach to system goals (Dinadis, Donati, Howie, & Janzen, 1995). The strategies for start-up may be categorized in three groups: mass input strategies, energy input strategies, and reservoir volume strategies. One of the principle rules guiding strategy selection appears to be to choose *the way of least resistance* (Rasmussen, 1981). This is implemented in terms of minimizing short term memory load. This thesis will examine in detail the mental strategies that the participants adopt, how these strategies affect their control performance, and reflect their mental models of the system.

1.2.2 Metacognition

"Metacognition is defined as the knowledge and control one has over one's thinking and learning activities" (Swanson, 1990, p. 306). This knowledge of cognition may be reflected either in its effective application or in a verbal description (Brown, 1987). Metacognitive processes can influence the use of mental strategies by providing an indication of how and when, where, and why different strategies are appropriate, that is, procedural and conditional knowledge. Further, metacognition can mediate between

[1] This use of the term *strategies* is consistent with the memory literature. However, in the problem solving and concept learning literature, strategies refer to general, domain independent procedures (Chi, 1987; Thorndyke & Stasz, 1980). According to these approaches, the strategies examined in this paper may be considered *procedures*.

strategy use and other influences such as motivation (Biggs, 1987; Carr, Alexander, & Folds-Bennett, 1994; Reeve & Brown, 1985).

Although the term is widely used, there remains a lack of consensus on what qualifies as metacognitive. Brown, Bransford, Ferrara, and Campione (1983) note that it is often difficult to differentiate the cognitive from the metacognitive. In addition, investigations of metacognition are carried out in two different research traditions: *knowledge about cognition*, and *regulation of cognition.* Brown et al. (1983) suggest that the term metacognition should be restricted solely to knowledge about cognition, where that knowledge is stable and statable or available to conscious reflection (Gleitman, 1987). Conversely, Chi (1987) recommends that only knowledge about strategies and procedures should be considered metacognitive. Chi (1987) suggests that labeling declarative knowledge about cognition as metacognitive obscures its similarity to declarative knowledge in other domains. However, she feels that knowledge about strategies is qualitatively different. In this case, *meta-* refers to second order knowledge, or rules about rules. Thus, both Brown et al. (1983) and Chi (1987) concede that the term metacognition is too broad, yet they offer differing ways of restricting its usage.

Metacognition is also related to the concept of *self-reflection.* According to Wright (1992), "metacognitive knowledge seems to involve reflective understanding of the process under consideration and of the actor's role in it" (p. 64). The role of self-reflection is indicated in studies of metacognitive training (Brown et al., 1983; Reeve & Brown, 1985). Blind training, in which the learners are not told what they are doing and why, results in only task-specific improvements. However, informed training, in which participants are informed of the reasons behind their training, results in improved transfer to other tasks.

There is a substantial volume of research demonstrating the benefits metacognition and self-reflection in learning (Brown et al., 1983; Thorndyke & Stasz, 1980). For example, Chi, Bassok, Lewis, Reimann, and Glaser (1989) found that good and poor students could be differentiated on the basis of the self-explanations that they produced while studying example physics problems. Good students exhibited more behavior that could be described as metacognitive. They generated many self-explanations relating to when a particular strategy should be used, and why. They also monitored the limits to their understanding. In contrast, poor students did not generate effective self-explanations, and they were not aware of gaps in their understanding.

Lawson and Chinnappan (1994) found that reflective activity was similarly important in the domain of geometry problem solving. High achieving students in their study included more frequent management statements than low achieving students, especially following the identification of errors or the generation of new information. These management activities included such activities as rereading the problem, planning, goal identification, checking, error correction and review.

Swanson (1990) found that students with both high metacognitive ability and high aptitude evidenced "a richer array of heuristic and strategy subroutines than other ability groups" (p. 312). However, regardless of aptitude, children with high metacognitive ability were more successful in solving pendulum and combinatorial problems than children with low metacognitive ability. Further, Chi, De Leeuw, Chiu, and LaVancher (1994) showed that self-explanations can promote learning of text-based material even when the explanations are prompted rather than spontaneously generated. Significantly, this advantage applied to both good and poor students equally. This thesis will examine whether the described relationship between metacognition and performance is applicable in the DURESS II environment during normal operating conditions.

Collins and Brown (1988) also emphasize the importance of self-reflection in improving problem-solving strategies. Further, they claim that computers can provide a medium for promoting reflection. Properly designed computer programs can provoke students to view their strategies from new perspectives, and to derive more abstract representations of their problem-solving behavior. The P+F interface for DURESS II is based on an abstraction hierarchy representation of the system. Thus, it provides more complete views of the system at various levels of abstraction, allowing the operators to view the system from different perspectives. The P+F interface also facilitates problem detection by explicitly indicating when system constraints are violated, potentially minimizing what Collins and Brown (1988) term *floundering*. Thus, it meets some of the conditions that Collins and Brown believe will promote reflection. This thesis will examine the extent to which the P+F interface facilitates reflection.

1.2.3 Cognitive Learning Styles

Cognitive styles are "individual consistencies in perception, memory, thinking, and judgment" (Messick, 1994, p. 121); they focus on the form of cognitive activity rather than the content. Learning styles refer to "a broad description of relatively consistent behaviors related to ways of going about learning" (Eysenck, 1994, p. 208). Learning styles also may be defined more narrowly as bipolar personality traits related to learning, a use more consistent with cognitive styles. The closely related concepts of cognitive styles and learning styles will be referred to collectively as cognitive learning styles. Learning approaches, or learning orientations, are learning styles that take into account situational influences, specifically motivational factors (Biggs, 1987; Entwistle, 1988; Schmeck, 1988a).

Cognitive learning styles should be distinguished from abilities (Messick, 1994; Riding & Pearson, 1994); cognitive learning styles are value differentiated, meaning that the opposite poles of a style dimension both have adaptive advantages and disadvantages. In contrast, abilities are value directional. Higher ability is both more desirable and more adaptive than lower ability. As well, cognitive learning styles apply across domains, while abilities are usually particular to a domain.

Strategies are also distinct from cognitive learning styles. When a person consistently uses similar strategies over a variety of different tasks and environments, this is an indication of a cognitive learning style (Schmeck, 1988a). Cognitive learning styles are relatively stable features of an individual, whereas strategies are variable across time and situations (Riding & Pearson, 1994). Similarly, Biggs (1988) states that "styles are focused on the person, strategies on the task" (p. 185).

Holism-serialism. Riding & Pearson (1994) have proposed the 'Wholist-Analytic Cognitive Style Family' in order to provide a conceptual structure for an array of cognitive learning styles. This is possible due to the considerable overlap between several cognitive learning style descriptions including field dependence-independence (Witkin et al., 1977), reflection-impulsivity (Kagan, 1965; Messer, 1976), uni-focus--

multi-focus (Driver, 1983), and holism-serialism (Pask & Scott, 1972; Pask, 1976, 1988). Not all instruments are equally appropriate for assessment within this cognitive style family. The validity of certain measures of field dependence-independence and reflection-impulsivity are questionable due to confounds with ability (Messick, 1994; Eysenck, 1994; Messer, 1976). However, measures of holism-serialism can provide a classification within this cognitive style family (Pask, 1974). (For further detail, refer to Howie, 1995.)

Serialists learn and remember information step-by-step. They focus narrowly on the details of a task, searching for small amounts of specific data. Serialists can be cautious, or fail to notice relationships. In contrast, holists learn and remember information as a whole. They are interested in the connections between topics. Holists tend to collect large amounts of information and view tasks with a broad focus. However, holists may be too impulsive, over-generalize, or jump to unwarranted conclusions (Pask & Scott, 1972). Learners that can adopt either a holist or a serialist strategy depending upon the situation are called versatile learners (Pask, 1976).

A practical implication of the holist-serialist distinction is that individuals learn most effectively when the teaching style matches their learning style (Pask & Scott, 1972; Pask, 1976). Further, both serialists and holists in a matched condition learn equally effectively. As an extension of this idea, it can be hypothesized that individuals may take advantage of the features of an interface that most closely match their learning style. The P+F interface makes the relationships between variables more explicit. Since holists are interested in the relationships between data, they may use this information more effectively. Further, the perceptual cues on the P+F interface can allow users to react according to the current state of the system rather than following fixed procedures. This also matches the holist approach more closely. The correspondence between features of the P+F interface and holism may translate into performance benefits for the holist participants (Howie, 1995).

Deep-achieving-surface approaches to learning. In addition to personality factors, the individual's perception of the situation is equally important in determining their performance. Bigg's (1987) approaches to learning take into account the relative roles of both of these factors. Deep, achieving, and surface approaches to learning are composed of strategy (personality) and motive (situation) combinations. These approaches were identified by a factor analysis of responses to Bigg's (1987) Learning and Study Processes Questionnaires (LPQ for secondary students, and SPQ for post-secondary students). Entwistle (1988) and Schmeck (1988b) have separately identified corresponding *learning orientations*, while Ng and Bereiter (1991) describe similar *goal orientations*.

Although various authors label their learning approaches differently, there is a great deal of agreement on attributes of the basic approaches. Students using a deep approach are intrinsically motivated and enjoy academic tasks; their strategies include trying to construct personal meaning from the task and seeking relationships with previous knowledge. They prefer loosely structured environments. Students using a surface approach are motivated by a fear of failure and see academic tasks as demands to be met. Their strategies include rote memorization, concentration on the surface features of a task, and viewing each element of a task as discrete and unrelated. These students prefer highly structured environments. Students using a deep approach concentrate on what an author means, whereas students using a surface approach concentrate on what the author says. Students using an achieving approach are motivated by high grades and competition. Their strategies involve well-organized study methods. The achieving approach is generally related to good academic performance and to students' satisfaction with their performance. However, these students may become too opportunistic, and do whatever is necessary to get high grades (Biggs, 1987).

Both the deep and surface approaches describe "ways in which students engage the context of the task itself, while the achieving strategy describes the ways in which students organize the temporal and spatial contexts surrounding the task" (Biggs, 1987, p.12). Biggs (1987) views these approaches to learning as independent ways of learning, not as the poles of a style continuum. Thus, it is possible to have composite learning approaches.

Metacognitive capacity increases from the surface approach to the deep approach, attaining an intermediate value with the achieving approach (Biggs, 1987). Thus, there should be some correspondence between measures of cognitive learning styles and the degree to which individuals are metacognitively oriented (as revealed by verbal protocols).

It can be hypothesized that the individuals' approaches to learning will also influence their performance while operating DURESS II. The abstraction hierarchy analysis ensures that the P+F interface provides a relatively complete representation of the system. In addition, there should be a consistent unique mapping between cues on an P+F interface and the constraints in the work environment. Thus, under normal operating conditions, individuals should be able to "get by" with a surface approach. However, individuals using a surface approach probably will not optimize their strategies. Further, the surface user is likely to lack the depth of understanding of the system that is necessary to diagnose and compensate effectively for a fault.

1.3 Aim

This thesis is one component of a larger research effort to evaluate the EID framework (Vicente, 1995). The data used in this study were collected and initially analyzed by Christoffersen et al. (1994b). The goal of this thesis is to further examine the cognition of the participants as they learn to operate the DURESS II simulation over an extended period of time using either a traditional interface including only physical information (P interface) or an ecological interface including both physical and functional information (P+F interface). In particular, this thesis will examine the participants' increasing expertise and adaptation to system constraints, and the role of individual differences in this development. Specifically, the thesis examines the following elements:

- the start-up strategies used by the participants and any effects of experience and interface type on these strategies
- the frequency of participants' metacognitive statements and any interaction between metacognition, interface type, and performance
- any interaction between interface type, individual participants' cognitive learning styles, and their performance.

1.4 Hypotheses

The hypotheses listed below arise both from the preceding theoretical discussion, and from an initial analysis of the data (Christoffersen et al., 1994b).

1. Participants will adapt to the goal relevant constraints within DURESS II with increasing experience.
2. Participants effectively using the P interface may exhibit more rigid, procedural strategies, while participants effectively using the P+F interface may exhibit more flexible, goal-oriented strategies reflecting a functional understanding of the system.
3. Participants expressing a larger number of metacognitive statements will exhibit superior performance.
4. Participants using the P+F interface will include more metacognitive statements in their verbal protocols than participants using the P interface.
5. Any performance benefit of the P+F interface will be moderated by individual learning or decision styles. Specifically, the following interactions are expected:
    a) Participants using a surface approach will focus mainly on perceptual cues from the P+F interface.
    b) Participants with a deep approach will use a wider variety of strategies, demonstrating adaptation to the context and greater functional understanding of the system.
    c) Holists will demonstrate better operating performance than serialists while using the P+F interface since it provides a better match to their learning style.

2. METHOD

2.1 Participants

The participants were 6 males ranging in age from 23 to 32 years. They each completed a demographic questionnaire to determine the number of courses they had taken in physics and thermodynamics, and their overall level of education. The participants were matched as closely as possible in pairs according to their educational background. One member of each pair was assigned randomly to the P+F interface group, and the other to the P interface group. The resulting groups are shown in Table 2.1. The pairs are indicated by the order within the lists (for example, AS and TL were matched). Note that these initial pairings were not used in any subsequent analyses.

Table 2.1. *Summary of Participant Groupings*

Interface	Subject	Educational background
	AS	Mechanical engineering (Master's level)
P+F	AV	Industrial engineering (Master's level)
	IS	Medical genetics (Ph.D. level)
	TL	Electrical engineering (Master's level)
P	ML	Commerce/political science (Bachelor's level)
	WL	Geophysics (Ph.D. level)

2.2 Materials

The DURESS II simulation ran on a Silicon Graphics IRIS Indigo R4000 Entry Level Workstation. The simulation code was written in C and the interfaces were designed using the FORMS graphical construction set. The verbal protocols were recorded using a Sony CCD-TR81 Hi-8 Handycam.

The participants were tested after the experiment using the 'Spy Ring History' test and the SPQ. These tests determine the participants' cognitive learning styles and approaches to learning respectively. (Refer to Appendix A for a description of these instruments.)

2.3 Procedure

The experiment was 6 months in duration and included a total of 224 trials per participant on the DURESS II simulation. On the first day, the participants read descriptions of the experimental procedure, completed a demographic questionnaire, and took a pre-test to examine their knowledge of thermodynamics. (For copies of these instruments refer to Christoffersen et al., 1994b).

The participants were introduced to the experimental tasks gradually during the first month. First, the participants learned to take the system from an inactive state to steady state (start up task). This task continued until the final participant's performance stabilized, such that the completion times for his four most recent trials were within 1.5 standard deviations of their mean -- a total of 22 trials. Then shut down and tuning tasks were progressively added. In shut down, the participants had to return the system to an inactive state. In tuning, the participants had to adjust the system to new steady state demands.

For the following five months, each trial consisted of start-up, tuning, and shut-down tasks performed contiguously. Faults were distributed randomly, and infrequently, throughout the trials (15 faults out of 224 trials). The participants gave verbal protocols on a roughly regular basis (every second or third week). Since the primary focus of the initial study was fault management, the verbal protocols were retained mainly for fault trials. (Appendix B indicates the trials for which verbal protocols exist.) For the final six trials, the participants switched to the other interface (transfer trials). This determined the degree to which their operating knowledge and practices were transferable.

Each trial had a different steady state demand pair to prevent the participants from adopting excessively simplified control methods. (The demand pairs for the trials of interest in this study are listed in Appendix B.) The participants were not informed of the results of each trial, although they could receive feedback by observing their times at any point in the trial, and any system failure messages displayed on the screen. These messages simply stated which component had failed (for example, "Reservoir 1 heated empty").

One year after the experimental period, the participants returned to complete the 'Spy Ring History' test and SPQ to determine their cognitive learning styles (holist-serialist) and approaches to learning (deep-surface-achieving) respectively (Pask, 1976; Biggs, 1987). Ideally, the participants should have completed these questionnaires closer to the experimental period. However, the delay should not have a major impact on the results of the assessments since cognitive learning styles generally remain stable over time (Witkin, Moore, Goodenough, & Cox, 1977). In addition, a second group of 16 experimental participants also completed theses tests. These participants had recently finished a series of trials using the DURESS II simulation (Hunter, 1995), allowing a second comparison of the interaction between individual difference measures and performance.

The data from trials near the beginning and end of the experiment were chosen in order to investigate differences in the participants' cognition as they gained more experience. These data included the first 22 trials and the last 20 non-fault trials from 5 months later. Further, only the start up portions of the trials were analyzed. This portion of the data provides a consistent base for comparison of the participants' strategies. Since strategies are specific to a particular task, it will not affect the analysis to disregard the tuning, shut-down, and fault data. (For an analysis of the tuning, shut-down, and fault data refer to Christoffersen et al., 1994b.)

2.3.1 Data Sources

Three types of data were generated for each participant:

- *Time-stamped log files.* Whenever a participant clicked the mouse, the simulation recorded the participant's control action, the time, and the current values of all the system variables. For each trial, these values were stored in a log file that may be analyzed using various tools.
- *Verbal protocols.* The verbal protocols were recorded on videotape so that the participants' comments could be viewed within the context of the corresponding control actions and the overall system state. Verbal protocols exist mainly for fault trials, however, when the fault occurred after start-up, the verbal protocols during start-up should not be influenced by the fault. The verbal protocols were transcribed

for trials in which protocols existed for the majority of the participants and no faults occurred during start-up. Coding is described in the results section.

- *"Dplayer" trial replay module*. Dplayer can play back a trial, showing the actual screen while control movements are highlighted with an arrow. The trials may be interpolated to show continuous movement between control inputs. It is also possible to fast forward or rewind. Dplayer provides a useful environment for reviewing individual trials.

2.3.2 Analysis Tools

Each log file was analyzed using a number of tools:

- *Action transition graphs.* Action transition graphs reveal sequential relationships in behavior. Each action (component) is represented by a node, and those nodes that are accessed in sequence are joined by a line. The thickness of a line joining any two nodes is proportional to the frequency of that transition (see Figure 2.1). Action transition graphs can illustrate changes in patterns of skill, providing a summary of the individual's understanding of the system on a trial-by-trial basis (Moray, Lootsteen, & Pajak, 1986).

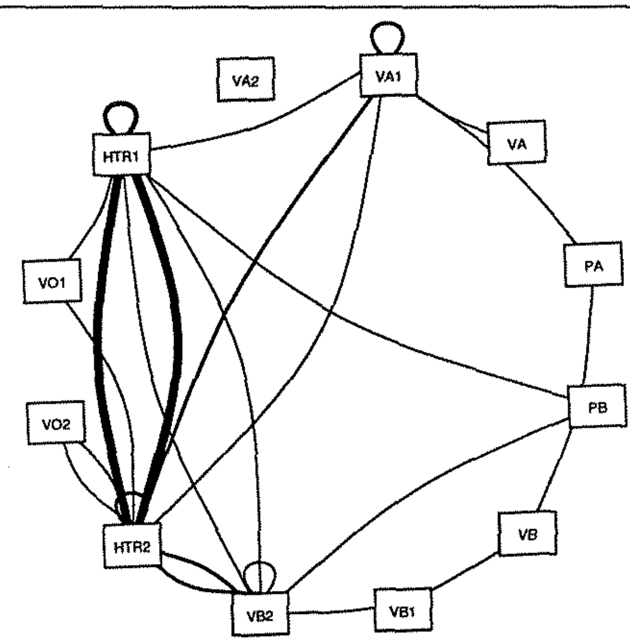

Figure 2.1 *Example Action Transition Graph.*

- *Clustering (ARC algorithm).* Clustering is defined as "the degree to which a subject performs actions that are designated to be of a particular category in a consecutive fashion" (Christoffersen, Hunter, & Vicente, 1994a, p. 8). Roenker, Thompson, and Brown (1971) developed the Adjusted Ratio of Clustering (ARC) in the context of free recall tasks. However, ARC scores are also useful in analyzing the grouping of control actions. Once all control actions are categorized using an independent, exhaustive set of groups, the ARC algorithm calculates a score between 0 and 1. A score of 0 indicates chance clustering and 1 indicates perfect organization of the participant's behavior according to a given grouping criteria. Multiple groupings may be used to determine which grouping criteria best match the clustering of control actions. The ARC scores may reveal a participant's strategies and how these strategies change with skill acquisition. However, ARC scores are limited to an average over a trial so that any changes of strategy *within* a trial will complicate this measure.
- *State space diagrams.* State space diagrams portray the system state with respect to the goal state. Thus, an individual's progress through the problem space may be graphically represented. The system states for each reservoir in DURESS II are plotted on a graph of temperature versus demand (see Figure 2.2). If both the temperatures and water outflows are normalized with respect to the goals, then the goal is reached when the demand and temperature both are equal to one. This allows the directness of the paths to the goal to be compared across trials with different goals. Therefore, state space diagrams provide another way of revealing the participants' strategies and skill acquisition. However, there is no representation of time in this measure, only of sequence or order.

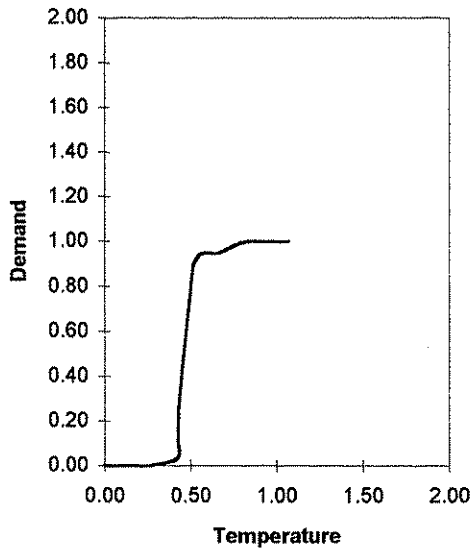

Figure 2.2 *Example State Space Diagram.*

- *Mass and energy inventories.* Graphs of mass inventory versus energy inventory provide an additional way of examining the system state with respect to the goal state. The ratio of energy inventory to mass inventory in a reservoir is proportional to temperature, as shown in the equation $E(t) = T(t)\ V(t)\ c_p$ rho

  where $E(t)$ = total energy stored in reservoir
  $T(t)$ = temperature of reservoir
  $V(t)$ = volume of reservoir
  c_p = specific heat capacity of water
  rho = density of water

  Therefore, the temperature goals appear as straight lines on the these graphs. These graphs can reveal the participants' strategies, and acquisition of expertise.
- *Timelines.* Timelines represent a sequence of actions over time. Each component of the system (Pump A, Valve A, Heater 1, etc.) is plotted against time on a common graph. Control inputs are indicated by points on the graph. Timelines may indicate strategies by showing the temporal relationship between control actions on various components. However, timelines do not indicate the extent of a particular change.
- *Information theory.* The information theory measure of entropy is defined as the "reduction of uncertainty" (Wickens, 1992). According to information theory, it is

possible to calculate the average information in a series of control actions. Across a series of trials, the more varied the sequence of control actions, the higher the average information. The average information may reveal the degree to which participants' control actions follow standardized procedures.

3. RESULTS

In this chapter, the analyses conducted and the resulting data will be described. First, behavioral evidence regarding the participants' mental strategies will be presented. This includes an examination of action transition graphs, clustering, state space diagrams, mass and energy inventories, timelines, and information. Second, the verbal protocol data will be analyzed to reveal additional evidence of the participants' mental strategies and degree of reflectivity. Finally, the participants' individual difference test results will be described and compared with several performance measures.

3.1 Behavioral Evidence of Mental Strategies

3.1.1 Action Transition Graphs

The action transition graphs reveal changes in the participants' skills similar to those found by Moray et al. (1986). Figures 3.1 and 3.2 show the action transition graphs for the participants on their first completed trial and on the last normal trial. The nodes represent each of the components in DURESS II, and the lines indicate which components were accessed in sequence. The graphs for each participant generally become less complex with experience, indicating both that the participants made fewer control actions and that their control actions were more sequentially consistent. In order to quantify this change, complexity was operationalized as the number of lines in the action transition graph (including repeated control actions involving the same component or "loops"). Table 3.1 gives the mean complexity for the initial and final blocks of trials. The mean complexity decreased for all but one of the participants, reaching significance for three of them (AS, IS, and WL).

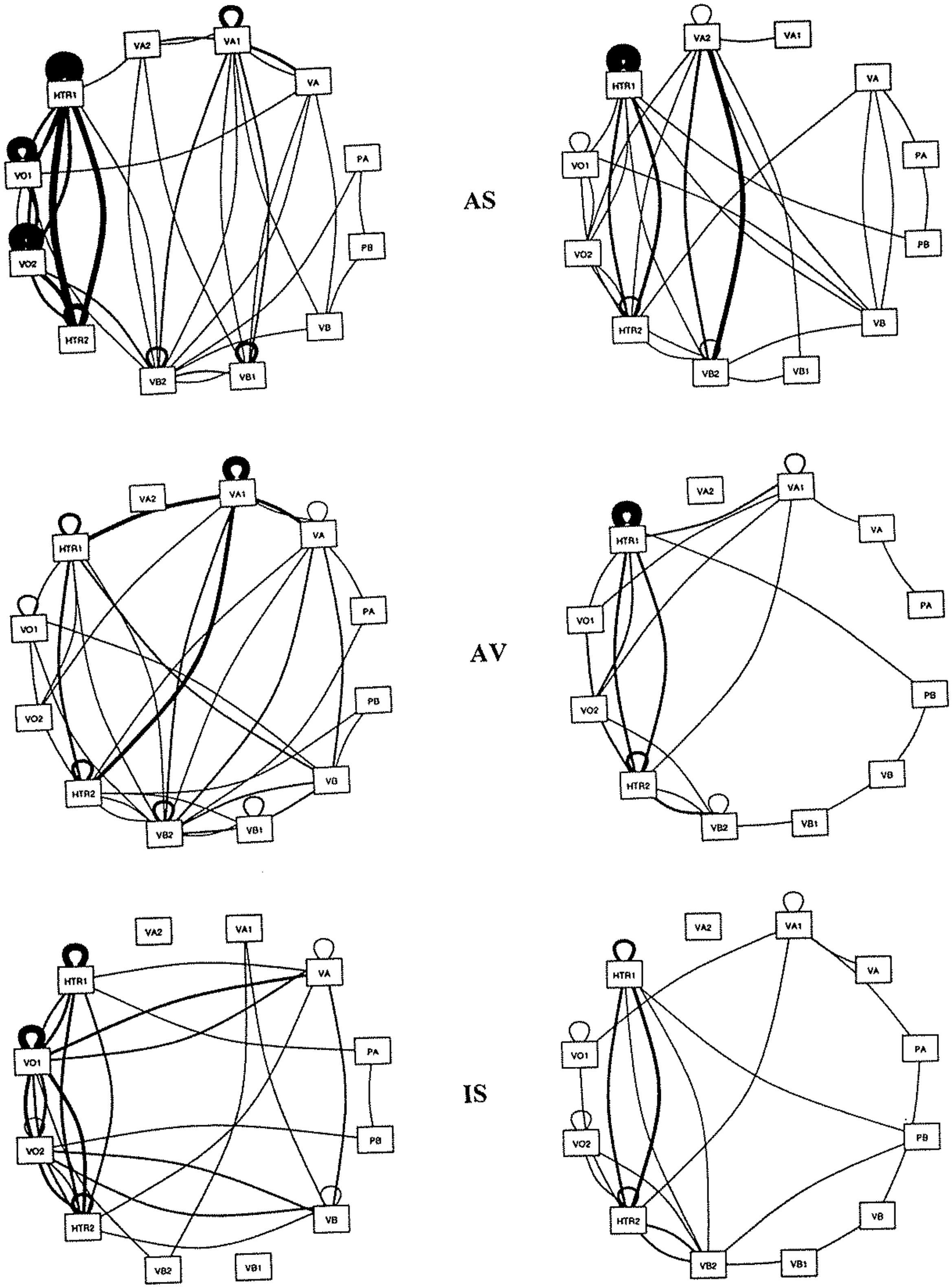

Figure 3.1 *Comparison of action transition graphs for first (left) and last (right) trial - P+F group.*

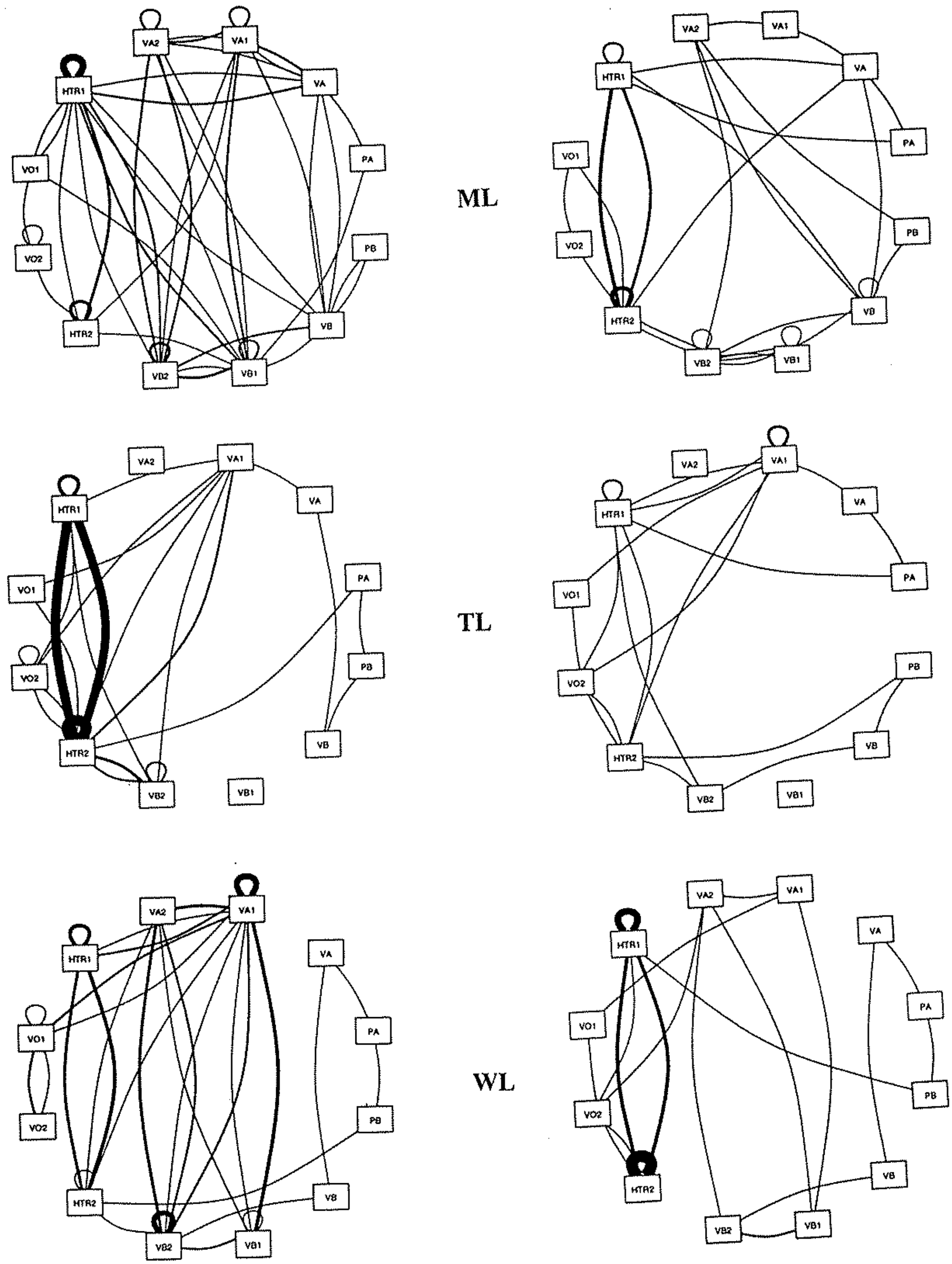

Figure 3.2 *Comparison of action transition graphs for first (left) and last (right) trial - P group.*

Table 3.1. *Mean Action Transition Graph Complexity*

		Complexity				
		Trials 1-22		Trials 196-217		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	48. 8	6.7	31.5	4.1	$t(31)= 8.72$ **
P+F	AV	24.6	3.8	23.4	3.5	$t(35)= 0.94$
	IS	25.2	4.4	22.0	3.8	$t(38)= 2.48$ **
	ML	31.0	6.8	28.3	4.6	$t(39)= 1.49$
P	TL	20.9	3.5	21.6	2.7	$t(34)= -0.67$
	WL	28.4	4.9	22.1	3.4	$t(33)= 4.42$ **
Mean P+F		32.3		25.2		
Mean P		27.1		24.1		

** $p < 0.01$

An ANOVA was completed on the first 20 and last 20 trials. The factors were Interface with repeated measures for each subject, and Block (early or late) with repeated measures for Trial. There was a marginally significant effect for Block ($F(1,4)=5.11$, $p=0.09$). An examination of the means revealed a decrease in the action transition graph complexity between the first and last blocks of trials (means of 29.7 for the first block and 24.7 for the last block). There was a significant effect for Trial ($F(19,75)=2.56$, $p<0.005$), reflecting significant differences in complexity across trials. There was also a marginally significant effect for Block x Trial ($F(19,49)=1.72$, $p=0.07$), reflecting the differing rates of change of complexity in each block of trials. The action transition graph complexity generally decreased between Trial 1 and Trial 20 in the first block of trials, however, the complexity was relatively constant between Trial 1 and Trial 20 in the second block of trials. There were no other significant results.

The mean steady state times for all of the participants also decreased significantly between the first and last block of trials (refer to Table 3.2). Steady state time is the time required for the participant to bring the system from a shut-down state to the goal state and to keep it within tolerance for five consecutive minutes. Thus, faster steady state times reflect the participants' increasing ability to reach the goals quickly, and to maintain the system in the goal state. Often those participants with less complex action transition graphs also had shorter trial times (compare Tables 3.1 and 3.2). In order to examine this relationship, the correlation between trial time and complexity was calculated. These correlations are shown in Table 3.3.

Table 3.2. *Steady State Times for Start-up*

		Steady state times				
		Trials 1-22		Trials 196-217		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	860.2	441.3	437.2	31.3	$t(31)= 3.70$ **
P+F	AV	517.3	149.0	353.5	16.11	$t(35)= 4.50$ **
	IS	644.4	125.8	399.0	17.5	$t(38)= 8.64$ **
	ML	660.3	261.8	390.2	48.0	$t(39)= 4.54$ **
P	TL	493.6	80.2	357.5	20.5	$t(34)= 7.16$ **
	WL	624.3	170.4	437.2	97.9	$t(33)= 3.95$ **
Mean P+F		664.0		396.6		
Mean P		592.7		395.0		

** $p < 0.01$

Table 3.3. *Correlation Between Action Transition Graph Complexity and Steady State Time*

		Correlation between complexity and steady state time	
Group	**Subject**	**Trials 1-22**	**Trials 196-217**
	AS	$r(16)= -0.22$	$r(13)= 0.12$
P+F	AV	$r(18)= 0.79$ **	$r(15)= 0.07$
	IS	$r(18)= 0.56$ **	$r(18)= -0.15$
	ML	$r(19)= 0.77$ **	$r(18)= 0.67$ **
P	TL	$r(15)= 0.43$	$r(17)= 0.59$ **
	WL	$r(16)= 0.56$ *	$r(15)= 0.12$

* $p < 0.05$. ** $p < 0.01$.

In the first block of trials, four of the six participants (two in each group) had significant correlations between complexity and steady state times for start-up. This probably reflects the "typical" result of simplification with experience described by Moray et al. (1986). As the participants improved over the first 22 trials, both their trial times and the complexity of their action transition graphs decreased.

In the second block of trials, there seems to be a difference between interface groups. Participants in the P+F group show almost no correlation between action transition graph complexity and trial times; however, there is a significant correlation for two out of three of the participants in the P group. This may be understood by considering action transition graph complexity as a measure of "procedural variety". A very complex action transition graph may show that participants rarely manipulate the same two components in sequence. A simple graph may indicate a rigid operating sequence, or procedure. Under this interpretation, these results suggest that rigid, procedural strategies are correlated with successful performance for participants in the P group, but not for participants in the P+F group. The P+F participants may successfully use more flexible strategies.

Between the first and last blocks of trials, the standard deviation of the steady state times also decreased substantially for all of the participants (refer to Table 3.2). Those participants who have shorter steady state times also have lower standard deviations for each block of trials ($r(10)=0.94$, $p<0.01$). Thus, participants with faster performance are generally more consistent. There is also a difference between interface groups. Participants using the P+F interface were more consistent than those using the P interface in the last block of trials (for a more detailed discussion see Christoffersen et al., 1994b).

Further, there is a relationship between the standard deviation of the trial times and action transition graph complexity. Participants with more consistent performance in each block of trials also have less complex action transition graphs ($r(10)=0.83$, $p < 0.01$). Thus, rigid, procedural strategies are correlated with more variable (or less consistent) performance. This relationship is stronger for the P+F interface group ($r(4)=0.88$, $p<0.01$) than the P interface group ($r(4)=0.71$, *n.s.*), and stronger for the first block of trials ($r(4)=0.98$, $p<0.01$) than the last block of trials ($r(4)= -0.05$, *n.s.*).

Mass input strategies. As well as revealing patterns of strategies overall, the action transition graphs demonstrated differences in the participants' mass input strategies. Several of the participants did not use all of the valves to control the system. Nodes VA2 (Valve A2) and/or VB1 (Valve B1) are unconnected in the action transition graphs for the participants AV, IS, and TL (refer to Figures 3.1 and 3.2). These valve minimization strategies indicate that these participants have a better understanding of the goal-relevant system properties.

According to a Cognitive Work Analysis of the DURESS II system (Dinadis, Donati, Howie, & Janzen, 1995), when neither demand exceeds 10 units/sec, it is possible to control the system using only four valves instead of six. This strategy significantly reduces the cognitive load on the users. Each demand can then be met by a completely independent feedwater stream. When either of the demands is greater than 10, the users need to use five valves at most. Controlling the system using all six valves is difficult due to the interactions between the components.

For each trial, it is possible to calculate the minimum number of valves needed to control the system. This number can then be compared to the actual number of valves that the participants used, in order to examine their sensitivity to this goal-relevant system property. The results are shown in Table 3.4.

Table 3.4. *Difference From Optimal Mass Input Strategy*

		Mean difference	
Group	**Subject**	**Trials 1-22**	**Trials 196-217**
	AS	1.72	1.67
P+F	AV	0.45	0.00
	IS	0.05	0.05
	ML	1.76	1.60
P	TL	0.18	0.00
	WL	1.72	1.65

Note. Difference from optimal mass input strategy = number of valves used less number of valves needed.

Clearly, those participants who used a valve minimization strategy adopted it early in the experimental period and continued to use it in the final block of trials. Further, AV, IS, and TL were very sensitive to the conditions under which the strategy could be used; in the final block of trials, these participants matched the valve configuration to the demand goals almost flawlessly, demonstrating near perfect adaptation. This adaptation was correlated with less variable performance but not with shorter trial times, as shown in Table 3.5. (In this calculation, the average steady state times and standard deviations for each participant were correlated with the mean difference from the 'optimal' valve input strategy over both blocks of trials).

Table 3.5. *Correlation Between Difference from Optimal Mass Input Strategy and Performance*

	Correlation
Steady state time	$r(10)=0.42$
Standard deviation	$r(10)=0.94$ **

Note. Difference from optimal mass input strategy = number of valves needed less number of valves used.
* $p < 0.05$. ** $p < 0.01$.

These findings confirm the results from the control recipes (Christoffersen et al., 1994). The way that the participants *described* their methods for controlling the valves conformed with how they *actually* controlled the system. Further, AV's control recipes differed from those of IS and TL since he did not give specific preconditions for using a particular valve configuration. AV merely stated that additional valves should be used "if necessary" to satisfy the demand goals. The results in Table 3.4 illustrate that this function-based orientation (as opposed to the action-based orientation of IS and TL) did not hamper AV's ability to use this strategy appropriately.

3.1.2 Clustering

Four different clustering groups were defined, forming a continuum from most context free (physical categorization) to most context specific (functional categorization):

Group 1	Individual components (PA) (VA) (VA1) (VA2) (HTR1) (VO1) (PB) (VB) (VB1) (VB2) (HTR2) (VO2)
Group 2	Physical component characteristics (pumps, valves, heaters) (PA PB) (VA VA1 VA2 VO1 VB VB1 VB2 VO2) (HTR1 HTR2)
Group 3	Components affecting volume in reservoir 1, those affecting volume in reservoir 2, and those affecting temperature. (PA PB) (VA VA1 VB1 VO1) (VB VA2 VB2 VO2) (HTR1 HTR2)
Group 4	Components affecting both reservoirs, those affecting reservoir 1, and those affecting reservoir 2. (PA PB VA VB) (VA1 VB1 VO1 HTR1) (VA2 VB2 VO2 HTR2)

The ARC scores reveal how closely the participants' consecutive actions match each of these grouping criteria. The higher the ARC score, the more closely the participants' actions are clustered according to the given grouping (scores range between 0 and 1). Table 3.6 shows that the ARC scores for grouping based on physical component characteristics (group 2) were the highest for all of the participants.

Therefore, most participants initially controlled the components in sequences based on their physical attributes. For example, the participants tended to manipulate valves in sequence rather than interspersed with actions controlling the pumps and heaters.

Table 3.6. *ARC Scores for Initial Block of Trials*

		Mean ARC scores (Trials 1-22)			
Group	**Subject**	**1**	**2**	**3**	**4**
	AS	0.41	**0.64**	0.50	0.38
P+F	AV	0.34	**0.48**	0.41	0.32
	IS	0.22	**0.55**	0.39	0.17
	ML	0.32	**0.54**	0.40	0.25
P	TL	0.19	**0.49**	0.47	0.21
	WL	0.31	**0.76**	0.54	0.24

Note. Bold indicates highest ARC score for participant.

For the final block of trials, there is a less consistent pattern (refer to Table 3.7). Fewer participants appear to be controlling the components in sequences based on their physical attributes. However, there does not appear to be a corresponding increase in behavior consistent with more functional groupings. Since the ARC scores are an average over the trial, perhaps changes in strategies within a trial complicate the measurement of behavioral clusterings.

Table 3.7. *ARC Scores for Final Block of Trials*

		Mean ARC scores (Trials 196-217)			
Group	**Subject**	**1**	**2**	**3**	**4**
	AS	0.22	**0.58**	0.38	0.19
P+F	AV	0.31	**0.38**	0.28	**0.38**
	IS	0.12	**0.31**	0.26	0.22
	ML	0.16	**0.54**	0.25	0.11
P	TL	0.15	0.21	0.14	**0.24**
	WL	0.36	**0.80**	0.61	0.32

Note. Bold indicates highest ARC score for participant.

The ARC scores for group 4, the most functional grouping, are the highest for two participants (AV and TL). These participants appear to be controlling the system based somewhat on the functional characteristics in the final block of trials. AV and TL also happen to be the most proficient participants in each interface group. This result is only suggestive, however, since there is no significant correlation between average steady state times and group 4 ARC scores (refer to Table 3.8). For the final block of trials, those participants who have lower ARC scores for the physical behavioral clustering (group 2) generally reach steady state more quickly (refer to Table 3.8). This would suggest that experienced users may benefit by controlling the system less based on its physical characteristics (and perhaps more based on its functional characteristics).

Table 3.8. *Correlations Between Average Steady State Time and Average ARC Scores*

	Correlations			
	1	**2**	**3**	**4**
Overall	$r(10) = 0.60$ *	$r(10) = 0.50$	$r(10) = 0.56$	$r(10) = 0.25$
Trial 1-22	$r(4) = 0.64$	$r(4) = 0.51$	$r(4) = 0.29$	$r(4) = 0.52$
Trial 196-217	$r(4) = 0.26$	$r(4) = 0.80$ *	$r(4) = 0.79$	$r(4) = -0.26$
P+F	$r(4) = 0.56$	$r(4) = 0.78$	$r(4) = 0.88$ *	$r(4) = 0.22$
P	$r(4) = 0.66$	$r(4) = 0.45$	$r(4) = 0.51$	$r(4) = 0.24$

* $p < 0.05$.

Control actions based on individual components (group 1) also correlate with slower steady state times overall. This is intuitively appealing, since those users who adjust a single component many times in sequence are less likely to be proficient in controlling the system. High scores in group 3 likely indicate that the participant is having difficulties stabilizing temperature. The significant correlation between steady state times and group 3 ARC scores may reflect the fact that participants who have trouble controlling the heaters will have longer trial times.

3.1.3 State Space Diagrams

Path length. State space diagrams reveal the directness of the participants' paths toward the goals through the problem space of water outflow (demand) versus temperature. The state space diagrams were plotted using values normalized by dividing each of the demand and temperature coordinates by the demand and temperature goals respectively. This normalization gives an equal weight to both demand and temperature, and allows meaningful comparisons across trials with different demand goals. The goal is reached when both the demand and temperature are equal to one. Figures 3.3 to 3.6 show the state space diagrams for the participants on their first completed trials and on the last normal trial. As could be expected, these paths appear to become more direct with experience. The paths for the P+F group also seem to be less direct initially than those for the P group, but become comparably direct with experience.

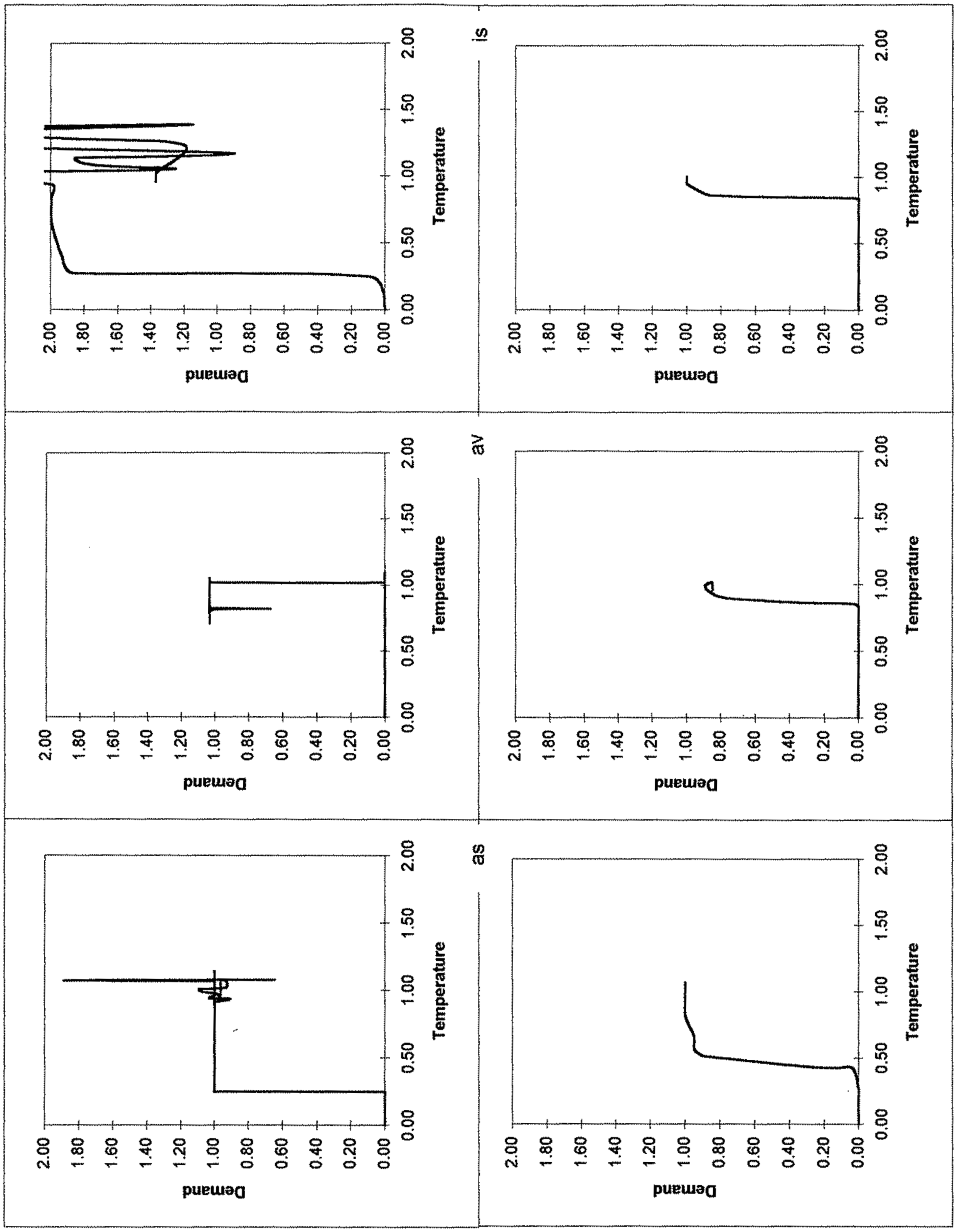

Figure 3.3 *Comparison of state space diagrams for first (top) and last (bottom) trial - P+F group reservoir 1.*

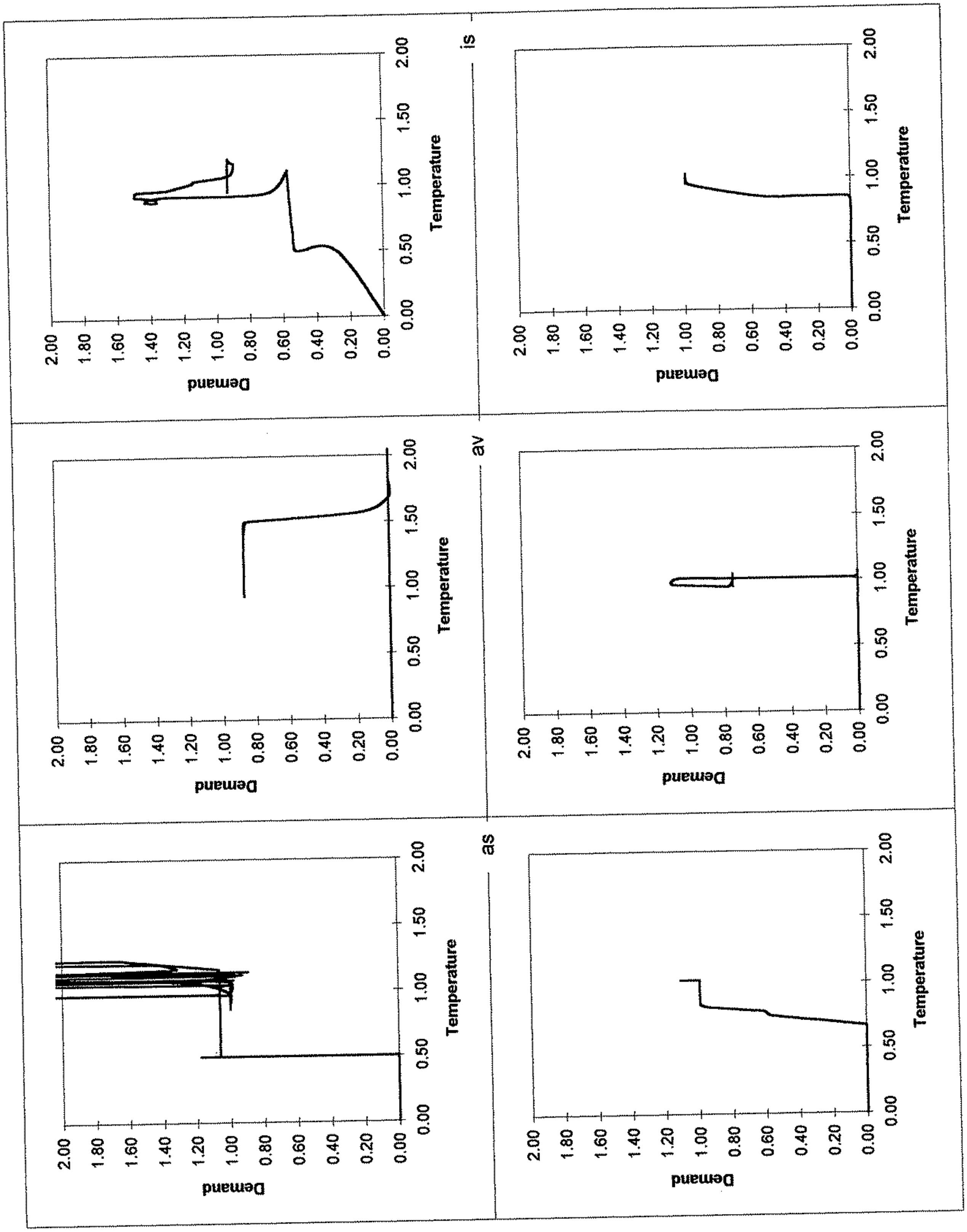

Figure 3.4 *Comparison of state space diagrams for first (top) and last (bottom) trial - P+F group reservoir 2.*

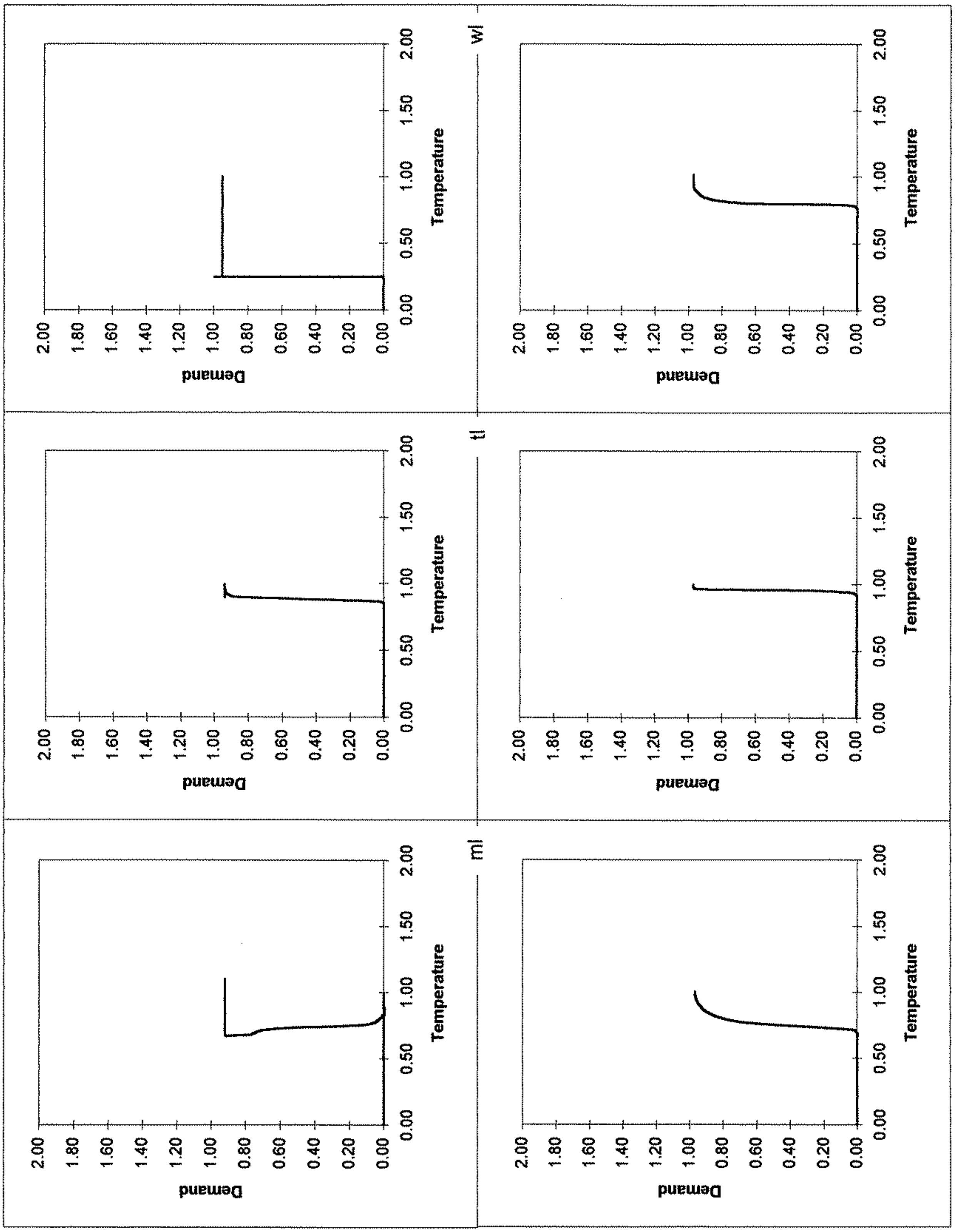

Figure 3.5 *Comparison of state space diagrams for first (top) and last (bottom) trial - P group reservoir 1.*

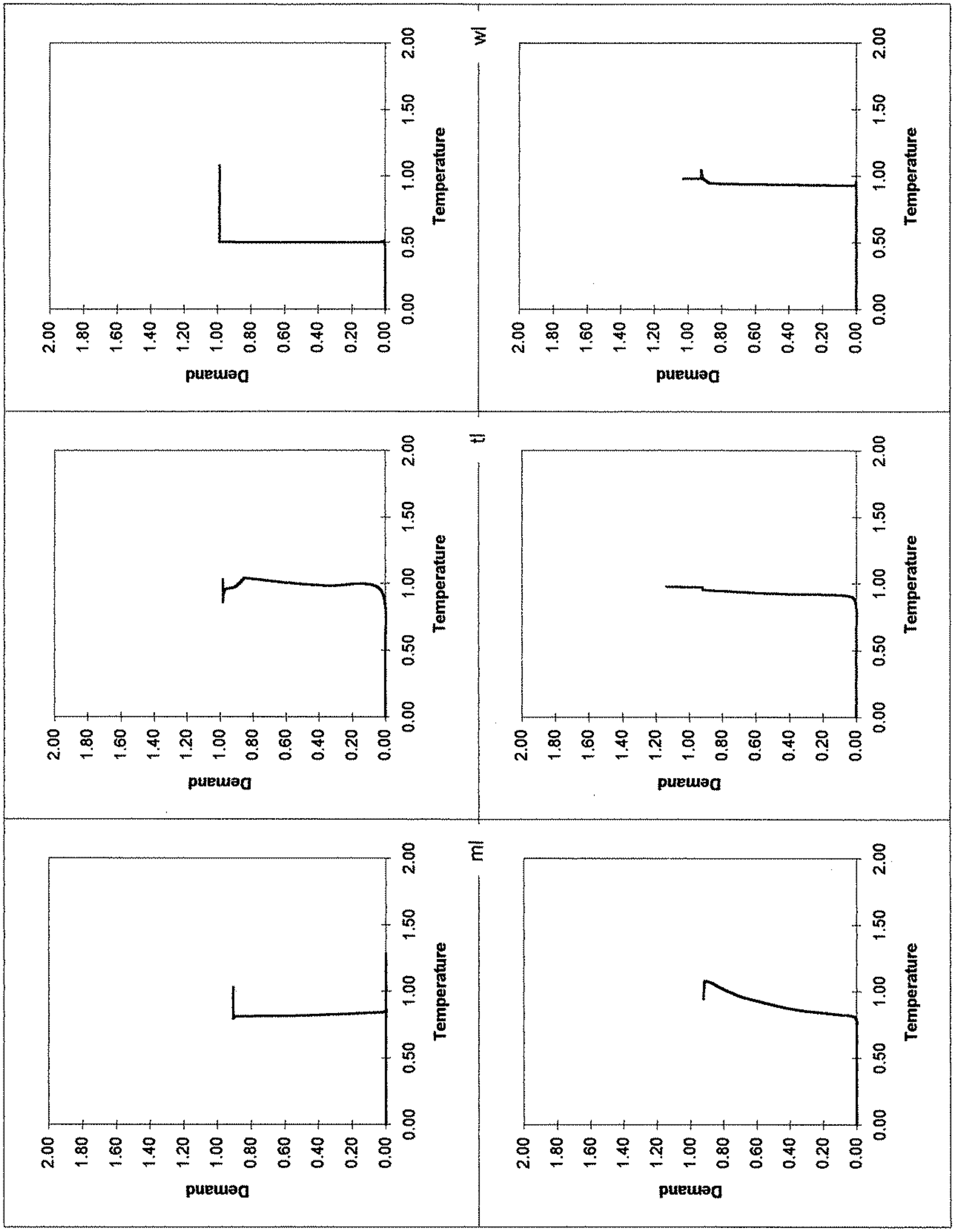

Figure 3.6 *Comparison of state space diagrams for first (top) and last (bottom) trial - P group reservoir 2.*

In order to make more quantitative comparisons, the length of a path in state space was used a measure of the directness of the path. However, one limitation of this method is that the path lengths are only linear approximations. Data points only occur whenever the participants made a control action. If the system state deviates appreciably from the linear approximation between control actions, the path lengths will be less accurate. Note, however, that this is highly unlikely since DURESS is a linear system.

Tables 3.9 and 3.10 give the mean path lengths for the initial and final blocks of trials for reservoirs 1 and 2 respectively. The mean path length decreased for all participants, with the exception of ML; however, this decrease was only significant for AS (both reservoirs) and TL (reservoir 2 only). The variance also decreased significantly between the first and final blocks of trials for all participants except for ML (both reservoirs) and AV (reservoir 1).

Table 3.9. *Mean Path Length for Reservoir 1 from State Space Diagrams*

		Path Length					
		Trials 1-22		**Trials 196-217**		**Mean**	**Variance**
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**	***F* ratio**
	AS	8.26	8.93	2.13	0.44	$t(31)= 2.56$ *	$F(17,14)=178$***
P+F	AV	2.59	1.19	2.50	0.88	$t(35)= 0.23$	$F(19,16)=1.84$
	IS	3.41	5.44	1.94	0.05	$t(38)= 1.21$	$F(19,19)=9896$***
	ML	2.48	0.63	2.99	1.96	$t(39)= -1.12$	$F(20,19)=0.10$
P	TL	3.00	3.78	1.99	0.08	$t(34)= 1.16$	$F(16,18)=2259$***
	WL	4.66	7.75	2.42	0.76	$t(33)= 1.19$	$F(17,16)=104$***
Mean P+F		4.65		2.23			
Mean P		3.40		2.36			

* $p < 0.05$. *** $p < 0.001$

Table 3.10. *Mean Path Length for Reservoir 2 from State Space Diagrams*

		Path Length					
		Trials 1-22		Trials 196-217		Mean	Variance
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**	***F* ratio**
	AS	9.08	10.5	2.32	0.66	$t(31)= 2.29$ *	$F(17,14)=33.77$***
P+F	AV	2.60	1.33	2.23	0.26	$t(35)= 1.13$	$F(19,16)=25.65$***
	IS	2.97	2.05	2.09	0.29	$t(38)= 1.90$	$F(19,19)=49.18$***
	ML	2.53	1.01	4.33	7.62	$t(39)= -1.07$	$F(20,19)=0.02$
P	TL	2.28	0.25	2.01	0.08	$t(34)= 4.24$ **	$F(16,18)=9.25$***
	WL	2.39	0.49	3.38	2.78	$t(33)= -1.48$	$F(17,16)=0.03$
Mean P+F		5.03		2.35			
Mean P		2.41		3.22			

* $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

An ANOVA was completed with the following factors: Interface with repeated measures for each subject, and Block (early or late) with repeated measures for Trial. The results are reported separately for each reservoir. For reservoir 1, there was a marginally significant effect for Block ($F(1,4)=5.94, p=0.07$). An examination of the means revealed a decrease in path lengths between the first and last block of trials for reservoir 1 (means of 4.04 for the first block and 2.30 for the last block).

For reservoir 2, there was a marginally significant effect for Interface x Block ($F(1,4)=5.99, p=0.07$), reflecting the different rates of change of path length in each block of trials. The P+F group experienced a decrease in path length between the first and last block of trials for reservoir 2, while the P group actually experienced an increase on average (refer to Table 3.10). There were significant effects for Block x Trial ($F(19,49)=3.65, p<0.0001$), and Interface x Block x Trial ($F(17,49)=3.93, p<0.0001$). The path lengths decreased more quickly between trial 1 and trial 20 in the first block of trials than in the last block of trials for reservoir 2. However, this rate of decrease depended on the interface. There were no other significant results.

The differences between the results for reservoirs 1 and 2 may indicate the role of attention. Often, particularly in the first block of trials, the path length for one reservoir is substantially longer than for the other reservoir (refer to Figures 3.3 and 3.4). It appears as if the participant is focusing on stabilizing one reservoir while the other drifts further from the goal.

Type of control. The state space diagrams also reveal the type of control strategy that the participants use. Even after extensive experience, the participants generally do not take the most direct route through the problem space to the goal. This would appear as a diagonal on the state space diagrams (length $\sqrt{2}$). The participants seem to first reach the temperature goal, and only then the water outflow goal (refer to Figures 3.3 to 3.6 for the final block of trials). A strategy where a participant first reaches one goal and then attempts to reach the second goal may be called a univariate control strategy (or single variable control). In order to have an indication of how closely the participants' behaviour conformed to a univariate control strategy, the actual path length was compared to an ideal univariate control path length of 2. Table 3.11 gives the mean differences for the final block of trials. Most participants have path lengths that are similar to those for univariate control. Indeed, participants IS and TL conform almost exactly to this strategy.

Table 3.11. *Mean Difference from Univariate Control Strategy for Final Block of Trials*

		Mean differences	
Group	**Subject**	**Reservoir 1**	**Reservoir 2**
	AS	0.13	0.32
P+F	AV	0.50	0.23
	IS	-0.06	0.09
	ML	0.81	2.45
P	TL	-0.01	0.01
	WL	0.42	1.38

Comparison between path length and steady state time. The correlations between steady state times and path lengths were calculated to determine whether participants who take less direct routes through the problem space (longer paths) also have longer steady state times. These correlations are given Table 3.12. There does not appear to be a consistent relationship between path lengths and steady state times.

Table 3.12. *Correlations Between Path Length and Steady State Time*

		Correlations			
		Trial 1-22		Trial 196-217	
Group	**Subject**	**Reservoir 1**	**Reservoir 2**	**Reservoir 1**	**Reservoir 2**
	AS	$r(16)= 0.47^*$	$r(16)= 0.85^{**}$	$r(13)= 0.77^{**}$	$r(13)= 0.18$
P+F	AV	$r(18)= 0.40$	$r(18)= 0.60^{**}$	$r(15)= 0.75^{**}$	$r(15)= -0.13$
	IS	$r(18)= 0.32$	$r(18)= 0.55^*$	$r(18)= 0.09$	$r(18)= 0.15$
	ML	$r(19)= 0.78^{**}$	$r(19)= 0.72^{**}$	$r(18)= 0.66^{**}$	$r(18)= 0.68^{**}$
P	TL	$r(15)= 0.31$	$r(15)= 0.40$	$r(17)= 0.70^{**}$	$r(17)= -0.01$
	WL	$r(16)= 0.03$	$r(16)= 0.16$	$r(15)= 0.28$	$r(15)= 0.06$

$^* p < 0.05$. $^{**} p < 0.01$.

Distance to goals. Data from the state space diagrams also can be combined with a representation of time by plotting the distance to the goals versus time. Distance to the goals was calculated for each reservoir using the following formula (note that all values are normalized with respect to the goals).

distance to goal = $\sqrt{((T - t)^2 + (D - d)^2)}$

where T is the temperature goal
t is the actual temperature
D is the water outflow goal (demand)
d is the actual water outflow

Figures 3.7 and 3.8 show graphs of distance to goals versus time for the participants on their first completed trial and on the last normal trial. These graphs reveal obvious improvements in the efficiency with which the participants approach the goals. Ideally, the participant would like to be within tolerance of the goals at the start of the trial (time = 0) and simply maintain this state for the required five minutes. This is not physically possible, since the system requires some time to get water into the reservoirs and heat this water to the goal temperatures. We can, however, obtain a measure of how far the participant deviates from this ideal by calculating the area under the graph. The closer the area is to zero, the better the participants' performance according to this criteria. Note, however, that the area under each graph is only an approximation. The area was calculated as the sum of the areas of rectangles with

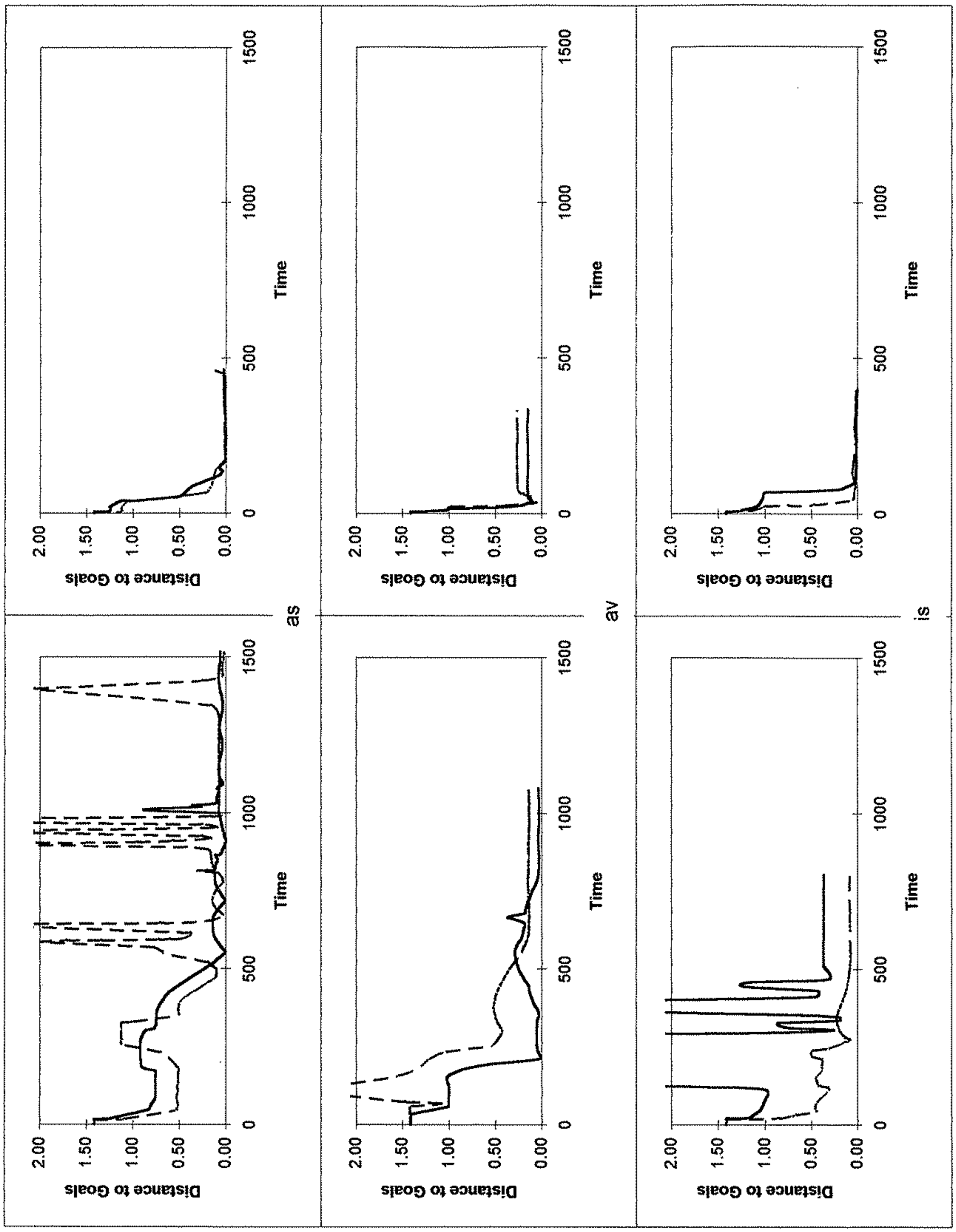

Figure 3.7 *Comparison of graphs of distance to goals versus time for first (left) and last (right) trial - P+F group (reservoir 1= solid line and reservoir 2 = dotted line).*

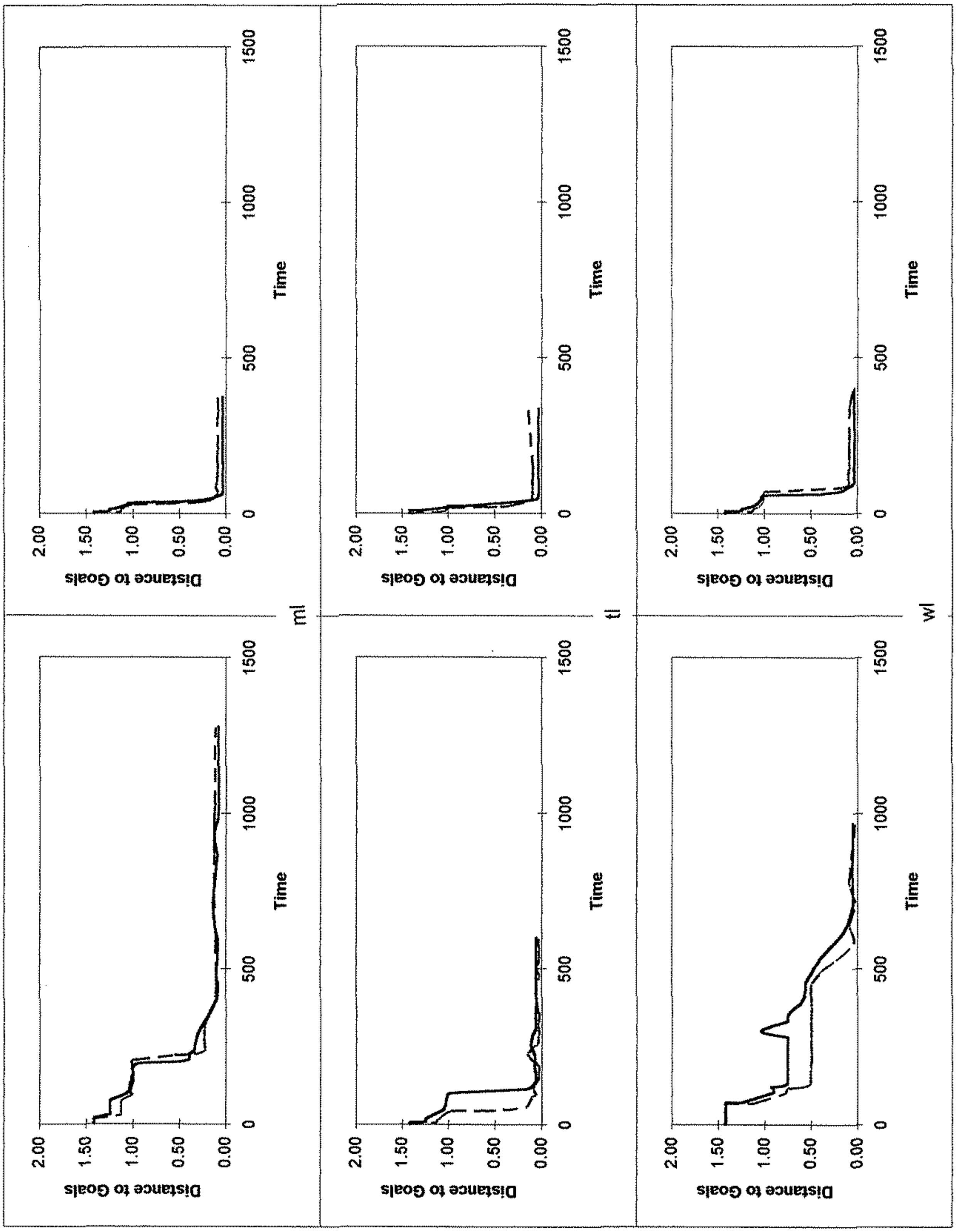

Figure 3.8 *Comparison of graphs of distance to goals versus time for first (left) and last (right) trial - P group (reservoir 1= solid line and reservoir 2 = dotted line).*

a width equal to the distance between control points, and height equal to the average height of the two control points bounding the rectangle. The further apart the control points, the greater risk that the areas may be less accurate.

Table 3.13. *Mean Area Under Distance to Goals versus Time Graphs for Reservoir 1*

		Areas				
		Trials 1-22		**Trials 196-217**		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	312.9	185.6	84.8	16.2	$t(31) = 3.25$ **
P+F	AV	118.2	65.4	64.9	16.3	$t(35) = 3.27$ **
	IS	234.2	207.9	77.1	14.9	$t(38) = 3.37$ **
	ML	165.9	117.4	66.6	18.6	$t(39) = 3.72$ **
P	TL	146.4	56.5	70.3	21.4	$t(34) = 5.46$ **
	WL	198.1	111.3	78.4	15.6	$t(33) = 4.39$ **
Mean P+F		221.8		75.6		
Mean P		170.1		71.7		

** $p < 0.01$.

Table 3.14. *Mean Area Under Distance to Goals versus Time Graphs for Reservoir 2*

		Areas				
		Trials 1-22		**Trials 196-217**		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	271.0	161.3	77.4	17.3	$t(31) = 1.92$
P+F	AV	123.3	115.0	61.4	15.2	$t(35) = 2.20$ *
	IS	176.6	50.6	66.5	53.5	$t(38) = 6.68$ **
	ML	131.3	90.8	80.1	73.4	$t(39) = 2.05$ *
P	TL	93.0	16.8	54.2	12.3	$t(34) = 7.94$ **
	WL	160.42	80.5	90.3	29.1	$t(33) = 3.39$ **
Mean P+F		190.3		68.4		
Mean P		128.2		74.9		

* $p < 0.05$. ** $p < 0.01$.

The areas under the distance to goals versus time graphs are given in Tables 3.13 and 3.14. Both the means and standard deviations of the areas decreased between the first and last block of trials. The decrease in means was significant for all of the participants with the exception of AS in reservoir 2. Thus, the participants improved with experience. Previously, steady state time has been used as the predominant measure of performance. In order to determine the degree of relationship between these performance criteria, the correlation between area under distance to goals versus steady state time was calculated. The results are shown in Table 3.15.

Table 3.15. *Correlations Between Area Under Distance versus Time Graph and Steady State Time*

		Correlations			
		Trial 1-22		Trial 196-217	
Group	**Subject**	**Reservoir 1**	**Reservoir 2**	**Reservoir 1**	**Reservoir 2**
	AS	$r(16)= 0.70^{**}$	$r(16)= 0.95^{**}$	$r(13)= 0.67^{**}$	$r(13)= 0.21$
P+F	AV	$r(18)= 0.73^{**}$	$r(18)= 0.86^{**}$	$r(15)= 0.55^{*}$	$r(15)= -0.16$
	IS	$r(18)= 0.37$	$r(18)= 0.76^{**}$	$r(18)= 0.73^{**}$	$r(18)= 0.22$
	ML	$r(19)= 0.92^{**}$	$r(19)= 0.93^{**}$	$r(18)= 0.84^{**}$	$r(18)= 0.92^{**}$
P	TL	$r(15)= 0.56^{*}$	$r(15)= 0.11$	$r(17)= 0.77^{**}$	$r(17)= 0.68^{**}$
	WL	$r(16)= 0.94^{**}$	$r(16)= 0.91^{**}$	$r(15)= 0.05$	$r(15)= 0.34$

$^{*}p < 0.05$. $^{**}p < 0.01$.

There is a significant correlation between the area under the distance to goals versus time graph and steady state times for all of the participants in most trial blocks. Thus, these performance criteria generally agree. This is not surprising since a longer trial time would usually increase the area. There is an added advantage to using area as a performance measure. One can examine the distance to goals versus time graph to obtain a more detailed view of the relationship between the performance within a trial and the outcome. In other words, the area provides a real-time measure, as opposed to the aggregate measure provided by the steady state times.

3.1.4 Mass and Energy Inventories

Mass inventory versus energy inventory graphs are similar to state space diagrams in that they provide a view of the system state with respect to the goal state. The temperature goals appear as straight diagonal lines on the these graphs since temperature is proportional to the ratio of energy inventory to mass inventory. By comparing the participants' trajectories through this space with the temperature goal line, we can obtain an indication of the participants' strategies and relative expertise. Figures 3.9 to 3.12 show the mass and energy inventory graphs for participants on their first completed trial and last normal trial. It is evident that the divergence of the participants' paths from the temperature goal line (dotted) becomes less with experience for all of the participants.

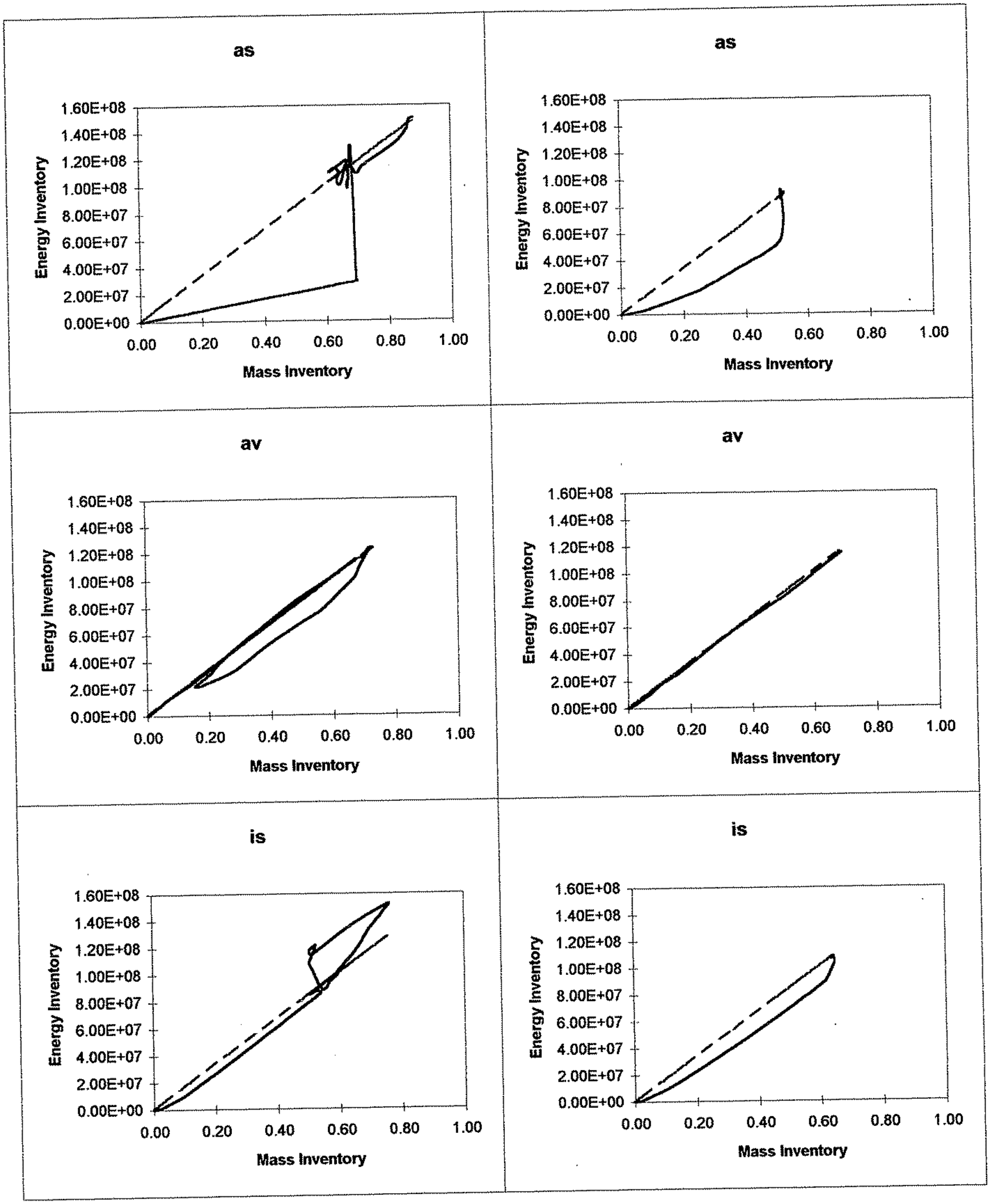

Figure 3.9 *Comparison of energy inventory vs. mass inventory graphs for first (left) and last (right) trial - P+F group reservoir 1.*

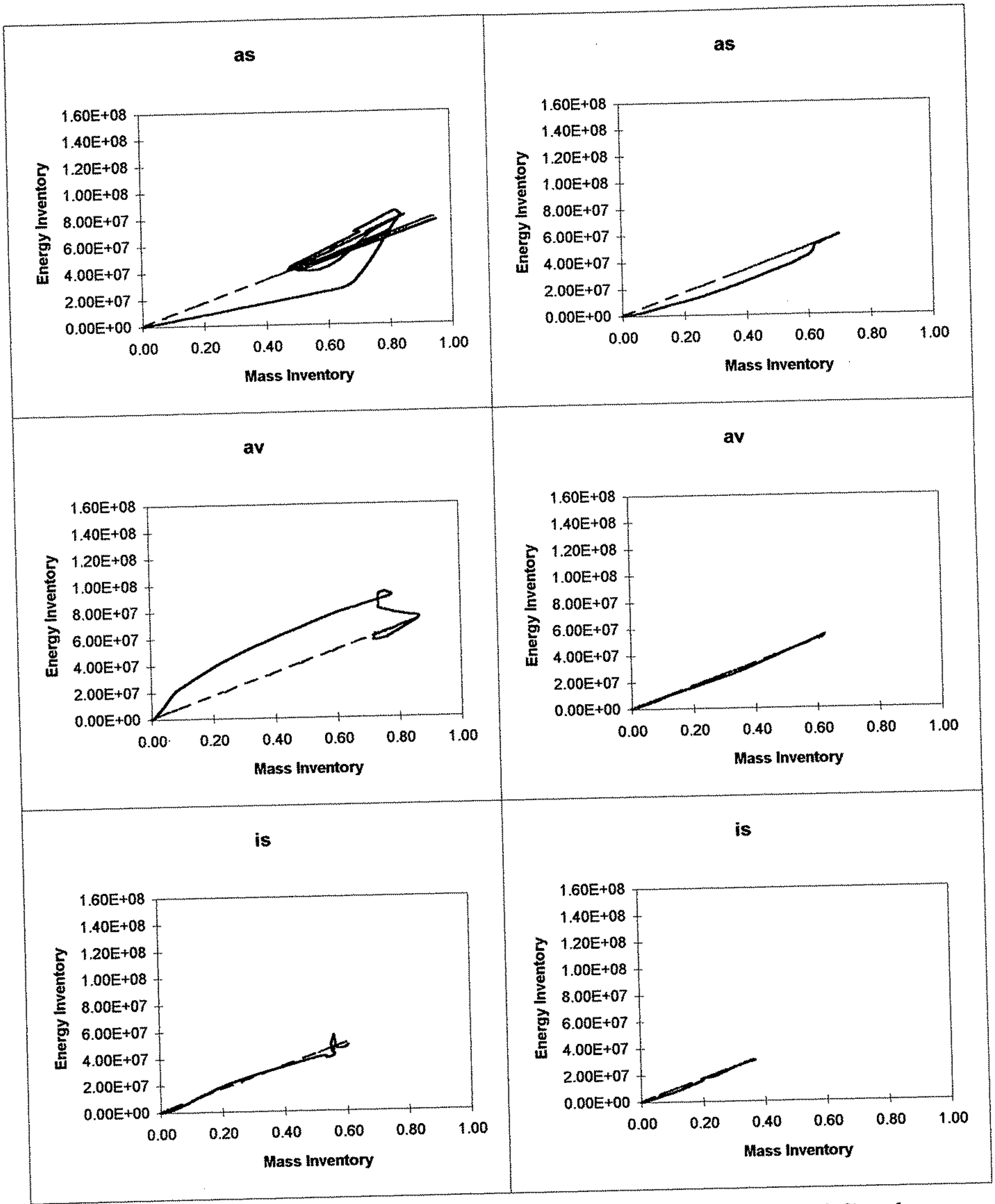

Figure 3.10 *Comparison of energy inventory vs. mass inventory graphs for first (left) and last (right) trial - P+F group reservoir 2.*

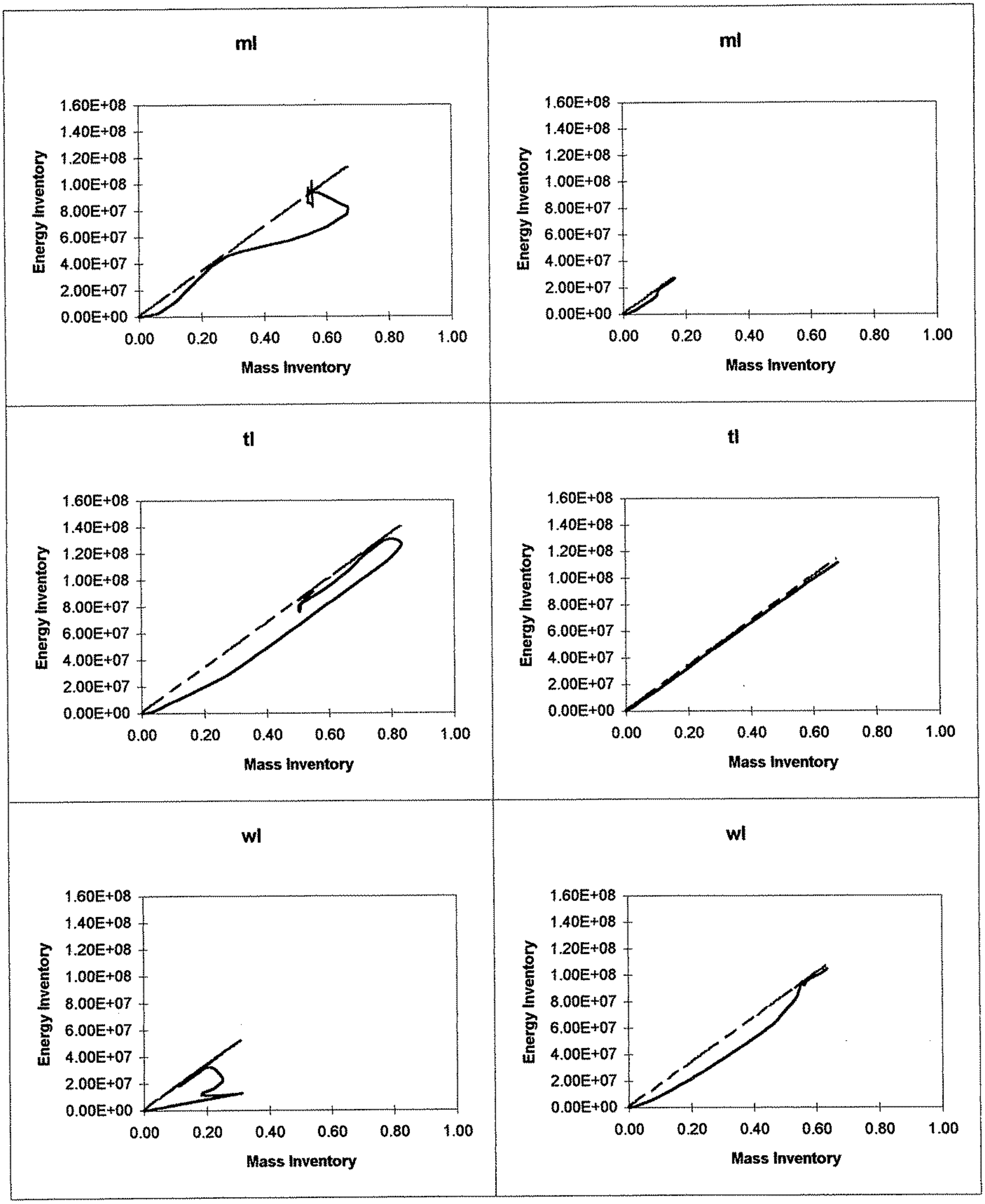

Figure 3.11 *Comparison of energy inventory vs. mass inventory graphs for first (left) and last (right) trial - P group reservoir 1.*

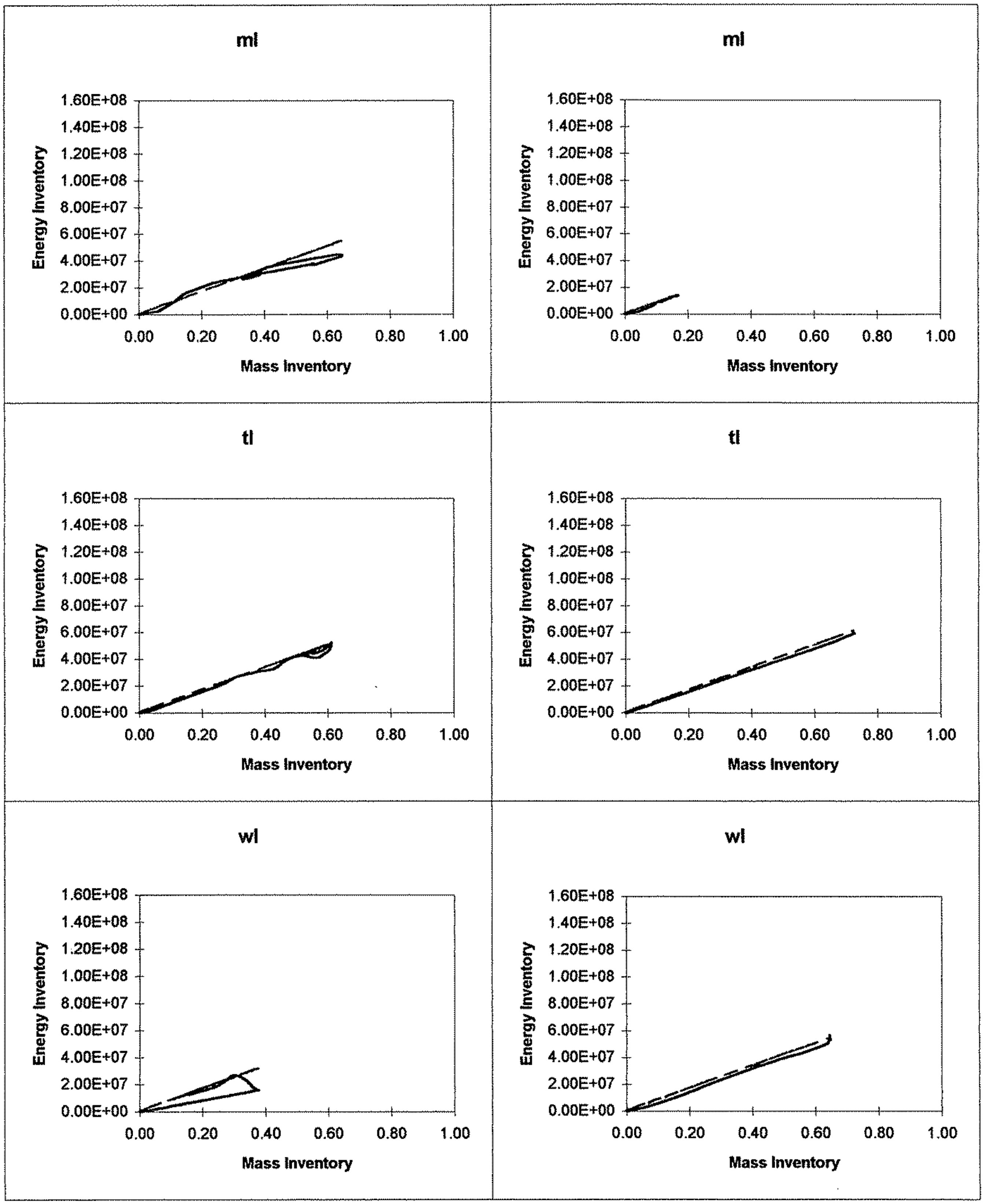

Figure 3.12 *Comparison of energy inventory vs. mass inventory graphs for first (left) and last (right) trial - P group reservoir 2.*

Further, a comparison of the mass inventory versus energy inventory graphs for different participants indicates their relative expertise. The participants AV and TL, who are generally the most proficient according to other measures (refer to Table 3.2 for trial times), also show the smallest deviation from the goal line. Indeed, these participants show a remarkable degree of adaptation to these system constraints. Both AV and TL track the goal lines very closely in the final block of trials. In contrast, the participants AS and WL, who exhibit generally lower scores on other performance measures, show a substantial deviation from the goal line even after 6 months of practice. As in other performance measures, IS and ML place between these extremes.

It is more difficult to quantify the relationships in these graphs since, unlike the state space diagrams, the goal on the mass inventory versus energy inventory graphs is not a point, but a line. Thus, there is no specific minimum distance between the starting point and the goal. The temperature goal may be met with differing reservoir volumes (mass inventories), and this is proportionately reflected in the energy inventory. Thus, when comparing the deviations from lines of unequal length, the area is confounded by the length. Further, the paths through these graphs may be non-monotonic on both axis. Therefore, measures of expertise are better obtained from other graphs derived from the mass inventory versus energy inventory plots, as described below.

Figures 3.13 to 3.16 show graphs of the <u>ratio</u> of energy inventory to mass inventory (E/M) versus time. In these graphs, the temperature goal line is indicated by a horizontal line. The participants' increasing expertise is demonstrated by the increasing speed with which they approach the temperature goals and the consistency with which they keep the system in this region.

The deviation from the temperature goal line can be quantified as the area between the system state and the temperature goal line. The area was calculated as a linear approximation, as described in the state space diagrams section. The areas of deviation from the temperature goal line are given in Table 3.16 and 3.17 for reservoirs 1 and 2 respectively. As expected, the mean area of divergence decreased significantly for all of the participants between the first and final blocks of trials. The standard deviations

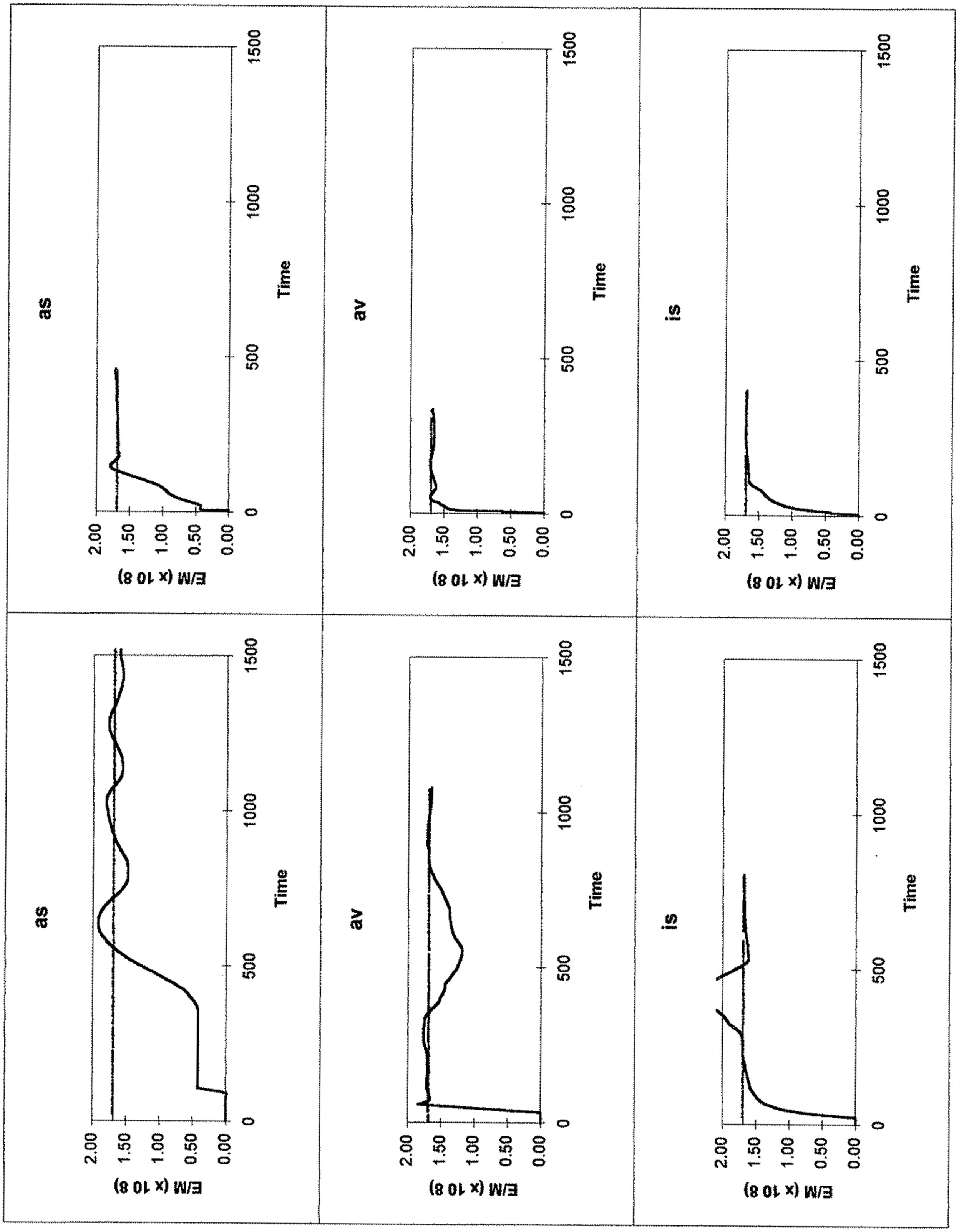

Figure 3.13 *Comparison of graphs of E/M vs. time for first (left) and last (right) trial - P+F group reservoir 1.*

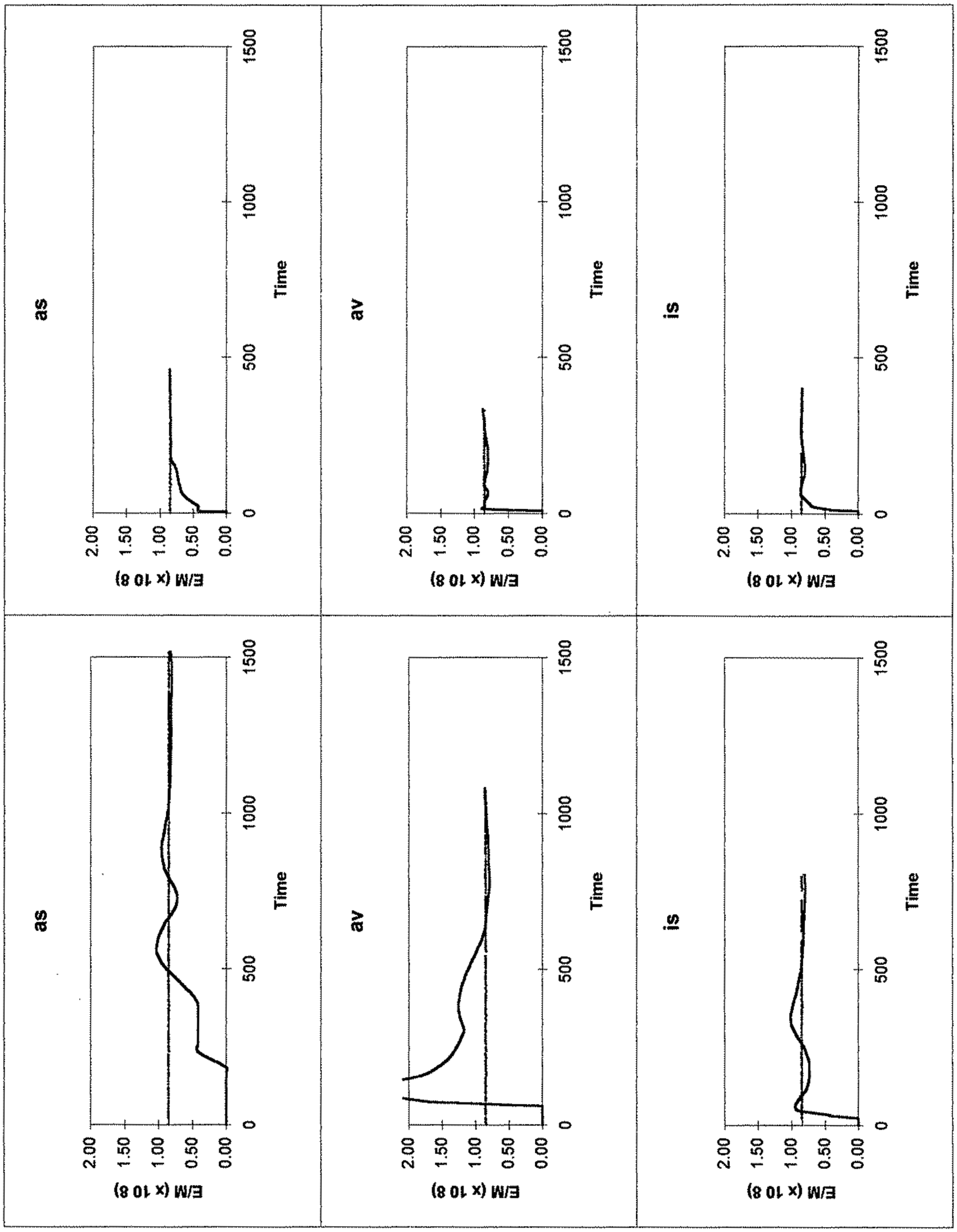

Figure 3.14 *Comparison of graphs of E/M vs. time for first (left) and last (right) trial - P+F group reservoir 2.*

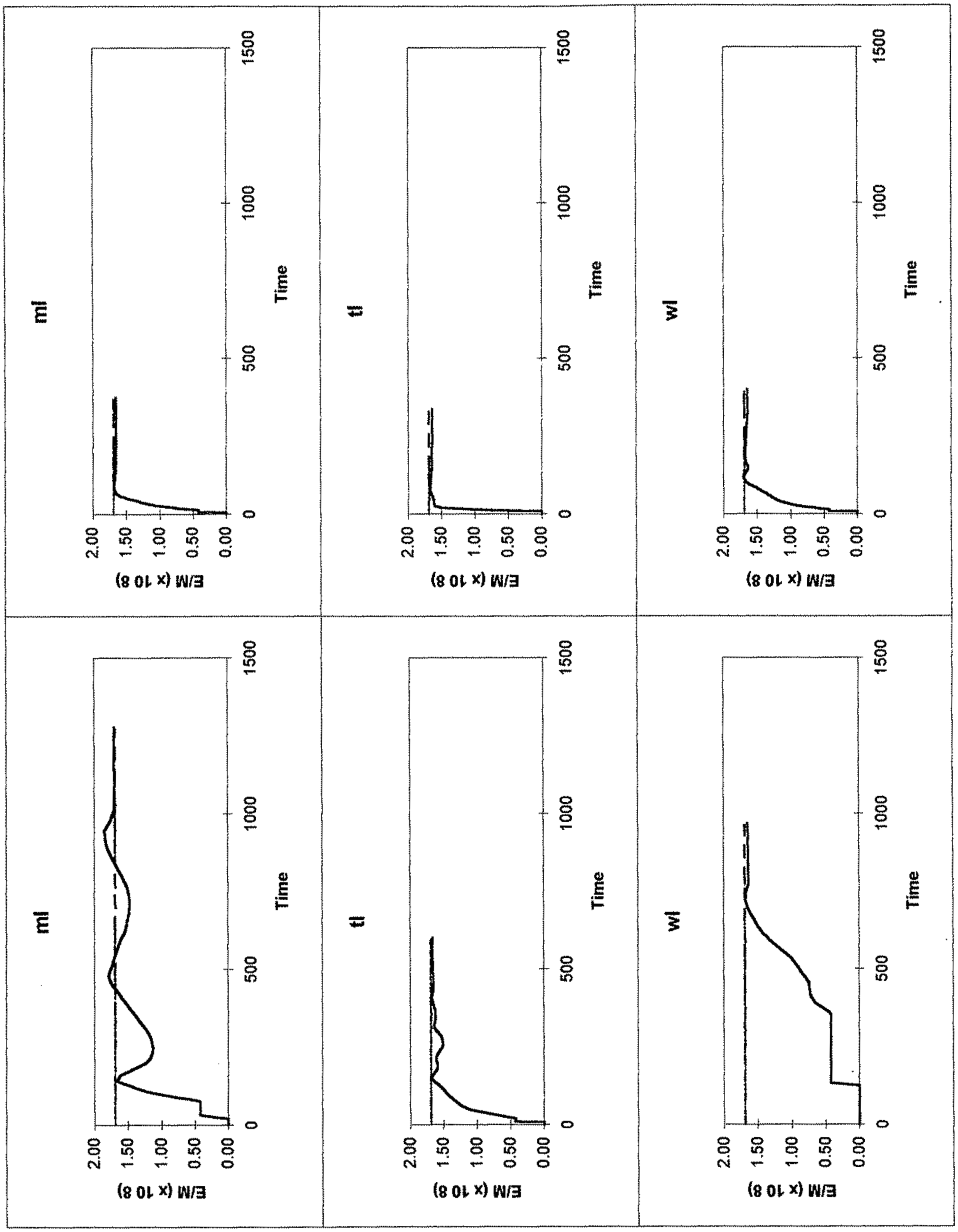

Figure 3.15 *Comparison of graphs of E/M vs. time for first (left) and last (right) trial - P group reservoir 1.*

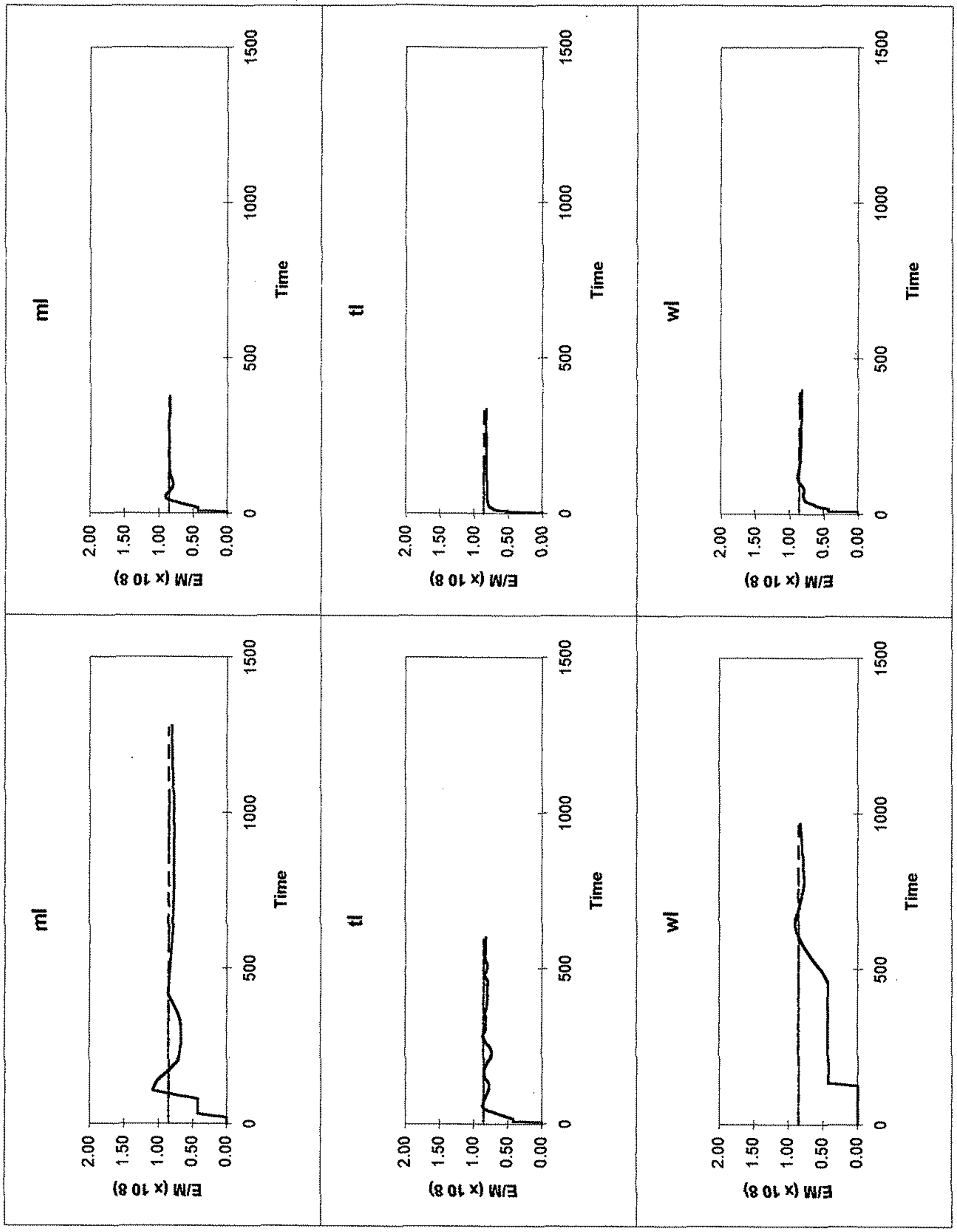

Figure 3.16 *Comparison of graphs of E/M vs. time for first (left) and last (right) trial - P group reservoir 2.*

also decreased for all of the participants. On average, the participants in the P+F group had a larger area of deviation from the temperature goal line than the participants in the P group during the first block of trials, although this difference only reached significance for reservoir 2 ($t(112)=1.83$, *n.s.* and $t(112)=2.65$, $p < 0.01$ for reservoirs 1 and 2 respectively). There was no significant difference between the P+F and P groups on this measure during the last block of trials ($t(106)=0.81$, *n.s.* and $t(106)=0.59$, *n.s.* for reservoirs 1 and 2 respectively).

Table 3.16. *Area of Deviation from Temperature Goal Line for Reservoir 1*

		Areas				
		Trials 1-22		**Trials 196-217**		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	361.0	223.6	89.4	18.0	$t(31)= 4.68$ **
P+F	AV	130.2	40.4	23.3	10.2	$t(35)= 10.62$ **
	IS	216.4	61.2	55.6	9.0	$t(38)= 11.62$ **
	ML	189.6	166.1	47.3	13.9	$t(39)= 3.82$ **
P	TL	74.2	15.9	42.1	12.7	$t(34)= 6.72$ **
	WL	257.0	186.9	66.6	9.0	$t(33)= 4.19$ **
Mean P+F		231.6		54.7		
Mean P		176.2		51.0		

** $p < 0.01$.

Table 3.17. *Area of Deviation from Temperature Goal Line for Reservoir 2*

		Areas				
		Trials 1-22		**Trials 196-217**		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	134.7	81.3	33.6	5.0	$t(31)= 4.80$ **
P+F	AV	78.2	71.8	16.3	3.3	$t(35)= 3.54$ **
	IS	80.7	14.5	19.7	3.7	$t(38)= 18.20$ **
	ML	61.9	40.0	21.5	12.7	$t(39)= 4.32$ **
P	TL	29.5	5.6	16.6	3.4	$t(34)= 8.50$ **
	WL	105.3	73.0	27.3	4.8	$t(33)= 4.39$ **
Mean P+F		96.6		22.6		
Mean P		66.0		21.6		

** $p < 0.01$.

Correlations between the area of deviation from the temperature goal line and the steady state time were calculated to determine whether participants who diverge very little from the temperature goal line also have shorter steady state times. Indeed this is the case, as shown in Table 3.18. This is not surprising since a longer trial time would usually increase the area. All of the participants except TL demonstrate a significant correlation in the first block of trials. Similarly, all of the participants except WL have a significant correlation in the final block of trials for at least one reservoir. Thus, the area of deviation from the temperature goal line can provide an additional indication of the participants' control effectiveness.

Table 3.18. *Correlations Between Area of Deviation from Goal Line and Steady State Time*

		Correlations			
		Trial 1-22		Trial 196-217	
Group	**Subject**	**Reservoir 1**	**Reservoir 2**	**Reservoir 1**	**Reservoir 2**
	AS	$r(16)= 0.78^{**}$	$r(16)= 0.84^{**}$	$r(13)= 0.94^{**}$	$r(13)= 0.49$
P+F	AV	$r(18)= 0.70^{**}$	$r(18)= 0.90^{**}$	$r(15)= 0.54^{*}$	$r(15)= 0.22$
	IS	$r(18)= 0.45^{*}$	$r(18)= 0.64^{**}$	$r(18)= 0.74^{**}$	$r(18)= 0.13$
	ML	$r(19)= 0.81^{**}$	$r(19)= 0.87^{**}$	$r(18)= 0.36$	$r(18)= 0.62^{**}$
P	TL	$r(15)= 0.46$	$r(15)= 0.21$	$r(17)= 0.80^{**}$	$r(17)= 0.64^{**}$
	WL	$r(16)= 0.91^{**}$	$r(16)= 0.91^{**}$	$r(15)= 0.00$	$r(15)= 0.42$

$^{*}p < 0.05$. $^{**}p < 0.01$.

Reservoir volume strategies. As stated previously, the temperature goals in DURESS II may be met with varying reservoir volumes (mass inventories). Therefore, we can examine the mean mass inventories that participants maintained at the end of each start-up trial. These values are summarized in Table 3.19 and 3.20. The mean final mass inventory decreased between the first and last blocks of trials for four of the participants (AS, IS, ML, and WL), and this decrease was significant for three of the participants (AS in reservoir 1 only; IS and ML in both reservoirs). The participants' shorter steady state times in later trials may be due to their decreased final mass inventories. During the first block of trials the participants generally waited for water to accumulate in the reservoirs therefore taking longer to stabilize the system (balancing the mass input and mass output).

However, the final mass inventory increased significantly between the first and last blocks of trials for two of the participants (AV in both reservoirs; and TL in reservoir 2 only). This may reflect a strategy adopted by these proficient users in later trials: they allowed additional water to accumulate in the reservoirs in anticipation of the shut-down task (refer to Christoffersen et al., 1994b). Therefore, AV and TL could turn off the heaters and let the water drain at the demand rate with little danger of heating an empty reservoir during shut-down (which would result in system failure).

Most of the participants maintained a mass inventory of approximately half the reservoir volume during the last block of trials. ML is a striking counter example since he maintained very low reservoir volumes. This strategy allows the system to respond to changes very quickly, however the system also becomes more unstable. This may account, at least in part, for the large standard deviations that ML displayed in many of the measures examined earlier (refer to Tables 3.10, 3.14, and 3.17 in particular).

Table 3.19. *Final Mass Inventory for Reservoir 1*

		Final mass inventory				
		Trials 1-22		**Trials 196-217**		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	0.79	0.11	0.50	0.10	$t(31)= 7.99$ **
P+F	AV	0.28	0.12	0.68	0.13	$t(35)= -9.54$ **
	IS	0.72	0.09	0.56	0.09	$t(38)= 5.52$ **
	ML	0.34	0.10	0.16	0.05	$t(39)= 7.13$ **
P	TL	0.57	0.17	0.65	0.06	$t(34)= -1.79$
	WL	0.51	0.11	0.48	0.12	$t(33)= 0.53$
Mean P+F		0.59		0.58		
Mean P		0.46		0.42		

** $p < 0.01$.

Table 3.20. *Final Mass Inventory for Reservoir 2*

		Final mass inventory				
		Trials 1-22		**Trials 196-217**		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	0.58	0.21	0.45	0.14	$t(31)= 1.99$
P+F	AV	0.28	0.13	0.67	0.13	$t(35)= -9.13$ **
	IS	0.72	0.09	0.34	0.06	$t(38)= 15.60$ **
	ML	0.36	0.13	0.21	0.07	$t(39)= 4.90$ **
P	TL	0.51	0.12	0.64	0.09	$t(34)= -3.95$ **
	WL	0.53	0.12	0.51	0.13	$t(33)= 0.31$
Mean P+F		0.52		0.51		
Mean P		0.46		0.45		

** $p < 0.01$.

In order to determine whether final reservoir volumes are related to performance, the correlation between final mass inventory and steady state time was calculated (Table 3.21). There is no consistent pattern of results. For some participants there was a significant positive correlation (AS, AV, IS, ML), for others a significant negative correlation (IS, WL), and for many participants these results differed between the blocks of trials. Thus, the relationship between final mass inventory and steady state time appears to be mediated by strategies and skill level -- or there is no relationship.

Table 3.21. *Correlation Between Final Mass Inventory and Steady State Time*

		Correlations			
		Trial 1-22		Trial 196-217	
Group	**Subject**	**Reservoir 1**	**Reservoir 2**	**Reservoir 1**	**Reservoir 2**
	AS	$r(16)= 0.26$	$r(16)= 0.48$*	$r(13)= 0.53$*	$r(13)= 0.37$
P+F	AV	$r(18)= 0.85$**	$r(18)= 0.80$**	$r(15)= -0.02$	$r(15)= -0.02$
	IS	$r(18)= -0.45$*	$r(18)= -0.48$*	$r(18)= 0.79$**	$r(18)= 0.20$
	ML	$r(19)= 0.47$*	$r(19)= 0.22$	$r(18)= -0.33$	$r(18)= 0.17$
P	TL	$r(15)= 0.05$	$r(15)= 0.12$	$r(17)= -0.29$	$r(17)= -0.11$
	WL	$r(16)= -0.42$	$r(16)= -0.58$*	$r(15)= -0.05$	$r(15)= 0.44$

* $p < 0.05$. ** $p < 0.01$.

An ANOVA was completed with the following factors: Interface with repeated measures for each subject, and Block (early or late) with repeated measures for Trial. For reservoir 1, there was a significant effect for Block x Trial ($F(19,49)=1.89$, $p<0.05$). The mass inventory decreased more quickly between trial 1 and trial 20 in the first block of trials than in the last block of trials for reservoir 1. There were no other significant results.

A further analysis was undertaken to investigate the role of the interfaces in shaping the reservoir volume strategy that the participants adopted. This was motivated by the *Heater Gain Problem* described by Pawlak (1994, p. 42).

> ... if the demand is low, then a low volume results in the temperature being more difficult to control. This difficulty arises from the fact that the small amount of water in the reservoir heats very quickly. Also, the goal temperature tolerance on the energy inventory, shown in the P+F interface, is very narrow, making it difficult to keep the temperature in the goal area. If the operator uses a high volume for a low demand, then the speed at which the water is heated is reduced,

resulting in more time being available for other control actions or decision making activities. Also, the goal temperature tolerance on the energy inventory, shown in the P+F interface, is wider with a high volume than it would be with a low volume, thereby facilitating control.

In analysis similar to that conducted by Pawlak (1994), the number of trials with final reservoir volume above 1/3 and below 1/3 capacity were calculated for each participant and pooled across interface groups. The results for the first block of trials are shown in Tables 3.22 and 3.23 for reservoirs 1 and 2 respectively. There was no significant difference between the interface groups during these trials, indicating that the initial reservoir volume strategies for participants in the P+F and P groups were comparable.

Table 3.22. *Chi Square for Reservoir 1 Volume, Trials 1-22*

	Number of trials final reservoir volume in range		
	Below 1/3	**Above 1/3**	**Total**
P+F	17	41	58
P	13	43	56
Total	30	84	114

Note. $\chi^2(1, N = 114) = 0.55$, *n.s.*

Table 3.23. *Chi Square for Reservoir 2 Volume, Trials 1-22*

	Number of trials final reservoir volume in range		
	Below 1/3	**Above 1/3**	**Total**
P+F	19	39	58
P	12	44	56
Total	31	83	114

Note. $\chi^2(1, N = 114) = 1.85$, *n.s.*

As shown in Tables 3.24 and 3.25, during the final block of trials, participants in the P+F group were more likely to maintain high volumes in reservoir 1 than participants in the P group. Apparently, the participants in the P+F group adapted to the constraints visible in their interface. With low reservoir volume, the energy goal tolerance is very narrow, making it difficult to maintain the energy inventory within the goal region. In contrast, with high reservoir volume, the energy goal region is broader, making the system easier to control. This constraint is visible on the energy inventory graphic of the P+F interface, however it is not explicitly visible in the P interface. Thus, the P+F interface preferentially facilitates adoption of a high reservoir volume strategy. The findings agree with those reported by Pawlak (1994) in a shorter term study.

Table 3.24. *Chi Square for Reservoir 1 Volume, Trials 196-217*

	Number of trials final reservoir volume in range		
	Below 1/3	**Above 1/3**	**Total**
P+F	0	52	52
P	22	34	56
Total	22	86	108

$\chi^2(1, N = 108) = 25.65, p<0.01$.

Table 3.25. *Chi Square for Reservoir 2 Volume, Trials 196-217*

	Number of trials final reservoir volume in range		
	Below 1/3	**Above 1/3**	**Total**
P+F	12	40	52
P	21	35	56
Total	33	75	108

$\chi^2(1, N = 108) = 2.64$, *n.s.*

It should be noted that this analysis involves a non-standard application of the Chi Square test since the results for the participants have been pooled according to interface groups (C. Bereiter, personal communication, December 18, 1995). This approach is a violation of the assumption of experimental independence unless the six subjects are considered as fixed. In this case, the results indicate the extent to which these results can be generalized to a larger population of trials. However, the findings can not be reliably generalized to a different population of participants.

3.1.5 Timelines

Timelines provide a way of visualizing a sequence of actions over time. Control actions are plotted against time on the horizontal axis, and are grouped according to the component acted upon on the vertical axis. Each time a component setting is changed, this control action is indicated by a point on the graph. Timelines do not indicate the magnitude of a particular change, but they preserve the order. These graphs provide another window on the strategies used by participants and their development of increasing expertise.

Figures 3.17 and 3.18 illustrate the timelines for the participants on their first completed trial and last normal trial for the P+F and P interfaces respectively. Immediately one can see that the trial times become shorter with experience, causing the control actions to be clustered closer to the y-axis in the later trials. Also the participants performed fewer control actions with experience. Further, the distribution of control actions within a trial changes with experience. In the final trials, the participants seem to have a larger *proportion* of their control actions near the beginning of a trial even when length of the trial is disregarded. These results conform to the observations of Moray et al. (1986).

In order to empirically evaluate the changing distribution of control actions, the percentage of control actions in the first quarter of each trial was calculated. The results are shown in Table 3.26. For all of the participants except WL, there was a significantly larger fraction of early control actions in the final block of trials compared with the first block of trials. Thus, not only did the participants have faster trial times, but they made an increasing proportion of their control actions earlier in the trials.

Table 3.26. *Percentage of Control Actions in First Quarter of Trial*

		% control actions in first quarter of trial				
		Trials 1-22		**Trials 196-217**		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	30%	6%	48%	10%	$t(31)= 6.15$ **
P+F	AV	45%	11%	70%	10%	$t(35)= 7.31$ **
	IS	36%	7%	65%	8%	$t(38)= 12.59$ **
	ML	47%	9%	83%	16%	$t(39)= 8.77$ **
P	TL	39%	8%	58%	11%	$t(34)= 5.87$ **
	WL	38%	6%	41%	10%	$t(33)=1.36$

** $p < 0.01$.

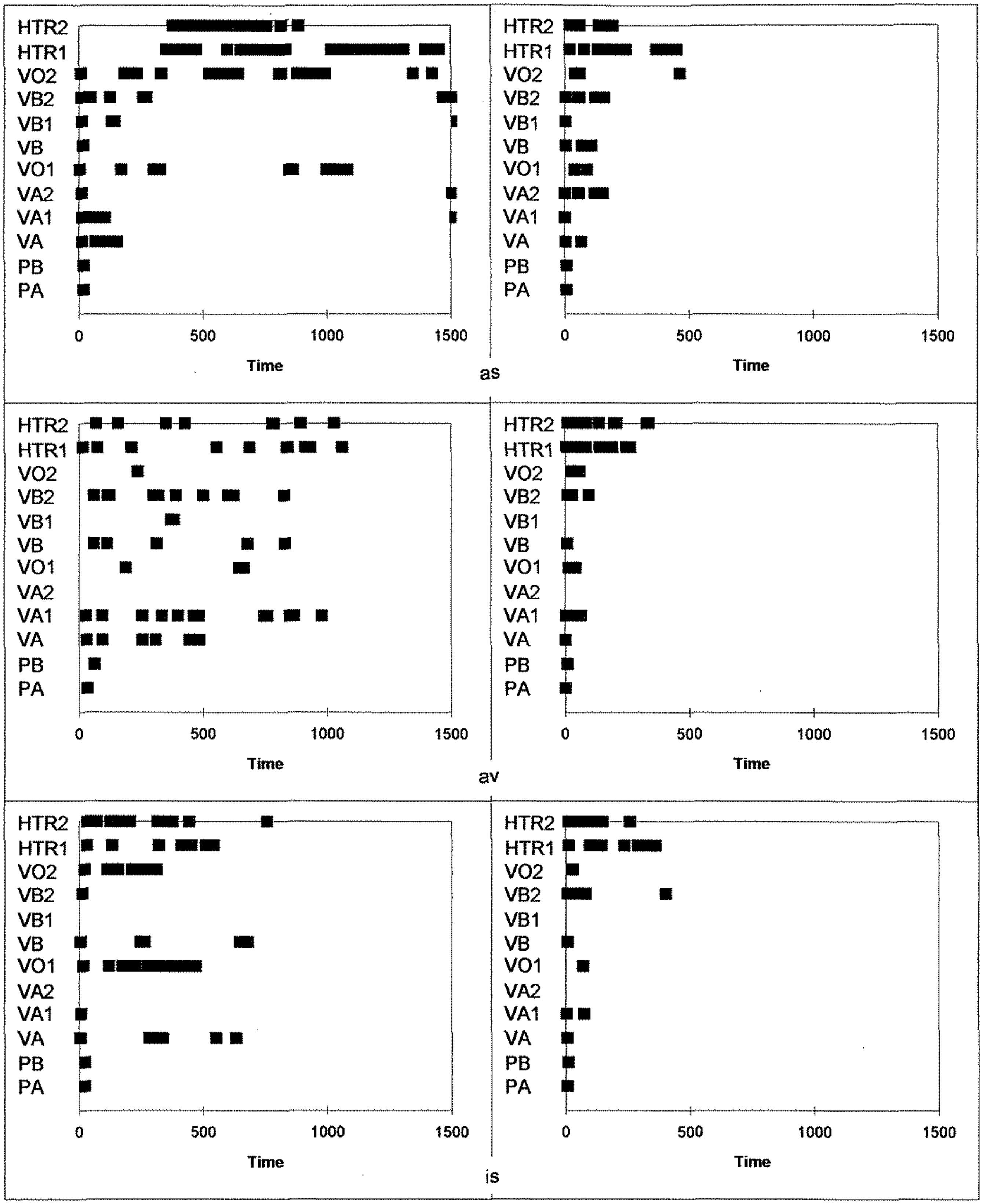

Figure 3.17 *Comparison of time lines for first (left) and last (right) trial - P+F group.*

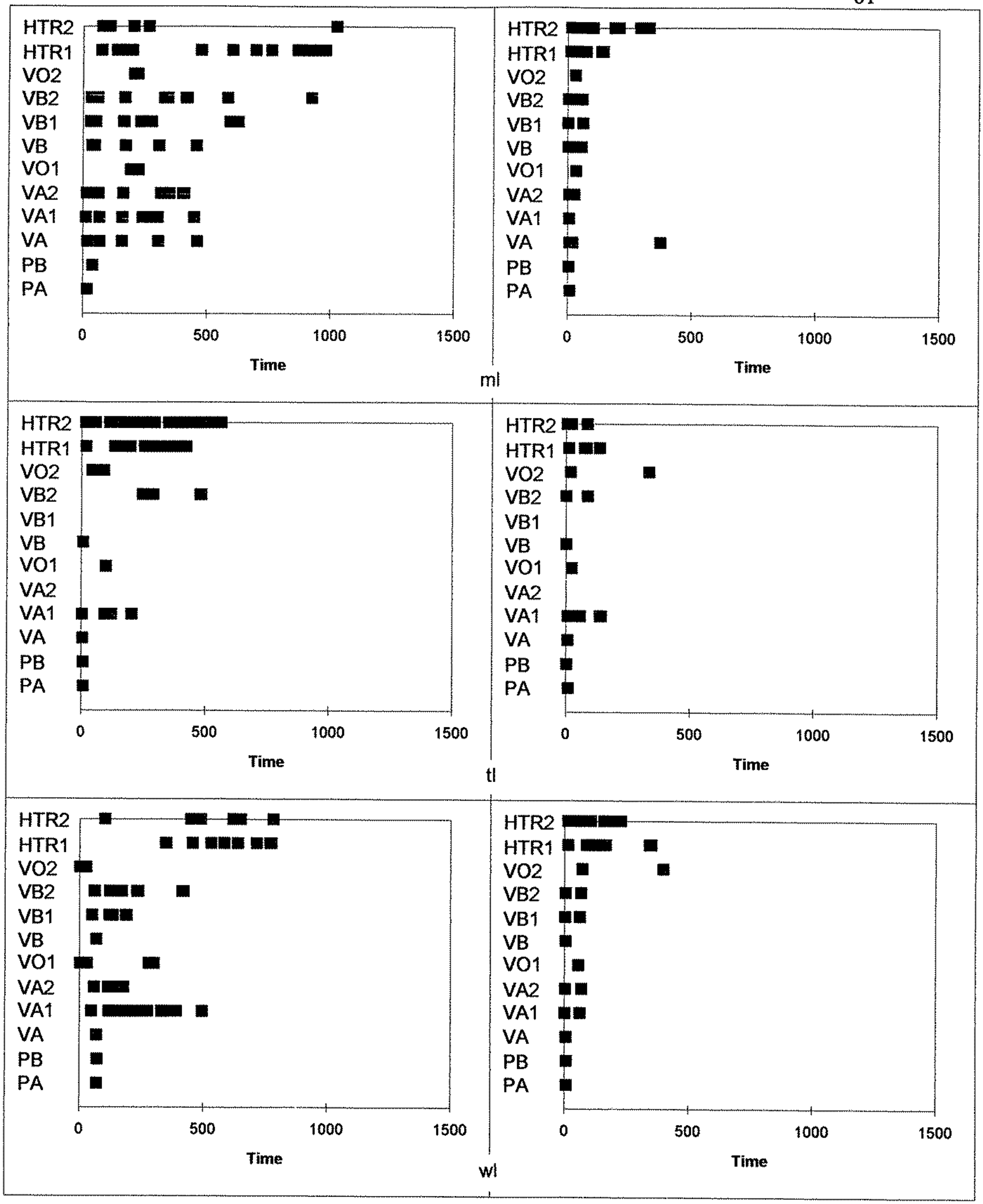

Figure 3.18 *Comparison of time lines for first (left) and last (right) trial - P group.*

There are large individual differences in the percentage of control actions in the first quarter of the trial (Table 3.26). Some of these differences can be traced to the participants' heater control strategies. Referring to Figures 3.18 and 3.19, it can be seen that many of the later control actions involve the heaters. To quantify this observation, Table 3.27 summarizes the percentage of the participants' control actions in the last three quarters of each trial that involve the heaters. The extreme scores in Table 3.27 are most illustrative. During the final block of trials, WL performed almost exclusively heater control actions in the final three quarters of each trial (96% on average). This was due to his trial and error method of heater control. According to his verbal protocols, WL chose "the best heating level to get the temperature stable" and then adjusted it repeatedly since "it takes a few tries to find the correct one" (WL Trial 63, appendix C). As a result, WL made substantially more heater control actions than the other participants (Table 3.28). WL did not increase the proportion of control actions that he made early in the trials, unlike the other participants, since he had to make continuous adjustments to the heaters throughout the trial (Table 3.26).

Table 3.27. *Percentage of Heater Control Actions in Final Three Quarters of Trial*

		% heater control actions in final 3/4 trial				
		Trials 1-22		**Trials 196-217**		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	48%	13%	77%	11%	$t(31)= -6.81$ **
P+F	AV	78%	16%	68%	24%	$t(35)= 1.38$
	IS	69%	17%	79%	10%	$t(38)= -2.19$ *
	ML	76%	18%	38%	32%	$t(39)= 4.80$ **
P	TL	86%	11%	56%	20%	$t(34)= 5.51$ **
	WL	79%	21%	96%	5%	$t(33)= -3.39$ **

* $p < 0.05$. ** $p < 0.01$.

ML falls at the other extreme. With experience, only 38% his actions in the latter part of each trial involved heater control (Table 3.27). By minimizing the percentage (and number) of heater control actions later in the trials, ML maximized the proportion of early control actions. In the final block of trials, he made an average of 83% of his control actions in the first quarter of the trial -- the highest proportion of all of the participants (Table 3.26). He achieved this high proportion by adjusting the heater settings according to a "rule of thumb" that he discovered through experimentation with the system (Christoffersen et al., 1994). Since the temperature goals for the two reservoirs are constant, the heater settings can be calculated as a ratio of the demands. Using this rule, ML set heater 1 to the same numerical value as the reservoir 1 demand, and heater 2 to one third of the numerical value of the reservoir 2 demand. This rule allowed ML to set the heaters to the appropriate level with little difficulty.

Table 3.28. *Number of Heater Control Actions in Trial*

		Number of heater control actions				
		Trials 1-22		Trials 196-217		
Group	**Subject**	***M***	***SD***	***M***	***SD***	***t* ratio**
	AS	48	17	31	8	$t(31)= 3.44$ **
P+F	AV	28	11	23	10	$t(35)= 1.49$
	IS	28	7	17	3	$t(38)= 5.81$ **
	ML	37	17	13	6	$t(39)= 5.90$ **
P	TL	33	9	14	6	$t(34)= 7.98$ **
	WL	43	22	54	20	$t(33)= -1.42$

** $p < 0.01$.

ML was not the only participant to determine that the heater settings can be expressed as a ratio of the reservoir demands. TL and IS also discovered this relationship (Christoffersen et al., 1994). In the final block of trials, the participants using this rule made fewer heater control actions than the other participants (Table 3.28). The mean heater number of control actions for ML, TL, and IS was 15.0, compared to a mean of 36.1 for the other participants. Thus, ML, TL, and IS demonstrated adaptation to this goal relevant constraint, and exploited it to minimize their heater control actions.

3.1.6 Information Theory

The control actions of a participant convey information since there is some uncertainty about what each control action may be. "Formally, information is defined as the reduction of uncertainty" (Wickens, 1992, p. 50). The maximum amount of information (H_{max}) in a series of control actions is set by the number of alternative stimuli (N), according to the formula below.

$$H_{max} = \log_2 N$$

In the case of DURESS II, there are 12 components that may be acted upon, and a range values at which the components may be set. The component settings were divided into bins of approximately one unit in width. Thus the valves or heaters may be set in 11 distinct regions (<0.5, 0.5 - 1.5, ..., > 9.5). The pumps have only two settings: on or off. Then there are a total of 114 alternative stimuli (2 x 2 pump settings + 10 x 11 valve or heater settings), resulting in a maximum value for information of 6.83 bits.

The actual amount of information in a series of control actions depends on the probability of occurrence of each event. Low probability events convey more information than high probability events since they have a greater impact in reducing uncertainty. The average amount of information in a series of control actions is given in the equation below.

$$H_{ave} = \Sigma_i P_i [\log_2 (1/P_i)]$$

The average information in a series of trials will depend both on the variability of control actions within trials and across trials. In this analysis, we are most interested in the latter component. If the participant controlled DURESS II in response to the particular goals and constraints present in each trial, their component settings should be more variable, and the average amount of information across a series of trials should be high. However, if a participant used a standard sequence of control actions, the average information should be lower. Thus, participants in the P group are expected to have lower average information across the final block of trials than participants in the P+F group.

The average information for the final block of trials was calculated for each participant. These values are shown in Table 3.29. In fact, there was no significant difference between the average information across interface groups (5.585 and 5.576 for the P+F and P groups, respectively). However, there were differences among the individuals. WL had the lowest average information, reflecting the fact that the majority of his control actions involved the heaters. This repetitive behavior lowered the average information across his final block of trials. In contrast, ML and AS had the highest values for average information. This may reflect their tendencies to use a trial and error control strategy, as discussed in Section 3.2.2.

Table 3.29. *Average Information in Final Block of Trials*

Group	Subject	Trials 196-217	
		Average Information	*Number of Control Actions*
P+F	AS	5.84	933
	AV	5.47	727
	IS	5.45	650
P	ML	6.10	769
	TL	5.44	586
	WL	5.19	1213

Due to the many factors that influence the average information, it is difficult to draw any firm conclusions. For example, low information may mean the subject is having difficulty controlling the system and needs to adjust the same components repeatedly. Alternatively, low information may mean that the participant has developed a routine or procedure for controlling the system which they execute each trial. High information may denote either a trial and error strategy, or sensitivity to the control actions required in the context of each trial. Thus, the same average information can convey different messages depending on the skill of the operator. It would be useful to derive another measure that more directly captures the degree to which a participant uses standard procedures across a series of trials.

3.2 Verbal Protocols

There were large individual differences both in the length and content of the verbal protocols. In the first section, the amount of verbalization will be compared, while the content will be examined in the following sections.

3.2.1 Verbalizations

The lengths of the protocols can be compared at two levels: words and phrases. The verbal protocols were divided into phrases at pause boundaries, where a pause boundary consisted of a natural break in speech. In order to normalize the protocols with respect to trial times, the results are reported in words per minute and phrases per minute. The averages across the nine verbal protocol trials are shown in Table 3.30 (for a list of verbal protocol trials, refer to Appendix B). The average amounts of verbalization were

27.1 and 27.9 words per minute (3.3 and 2.6 phrases per minute) respectively for the P+F and P groups. Thus, the average amount of verbalization did not differ significantly between interface groups ($t(49) = -0.13$, *n.s.* and $t(49) = 1.72$, *n.s.*, for words and phrases per minute respectively). However the amount of verbalization was significantly more variable in the P group than in the P+F group. Specifically, the standard deviation was 12.5 words per minute (1.3 phrases per minute) for the P+F group and 26.7 words per minute (2.0 phrases per minute) for the P group ($F(24,25) = 4.60, p < 0.05$, and $F(24,25) = 2.43, p < 0.05$, for words per minute and phrases per minute respectively).

Table 3.30 *Individual Differences in Average Amount of Verbalization per Minute*

Group	Subject	Time	Words/min.		Phrases/min.	
			M	***SD***	***M***	***SD***
	AS	381.3	26.9	9.8	2.6	0.7
P+F	AV	344.4	18.9	11.4	3.1	1.3
	IS	410.6	34.6	12.0	4.2	1.3
	ML	388.0	33.3	32.0	3.6	2.7
P	TL	415.7	37.4	28.2	2.8	1.5
	WL	384.6	14.1	15.4	1.3	1.3
P+F			27.1	12.5	3.3	1.3
P			27.9	26.7	2.5	2.0

A comparison of the lengths of the verbal protocols revealed a significant relationship between the number of words or phrases and trial time ($r(49) = 0.36, p < 0.01$ and $r(49) = 0.42, p < 0.01$, respectively). However, there is no significant correlation between the number of words or phrases *per minute* and trial time ($r(49) = -0.04$, *n.s.* and $r(49) = -0.10$, *n.s.*, respectively). Thus, the participants who had longer trial times had more time to verbalize, but they did not verbalize more frequently on average in any given time period. Thus, verbalization per se does not appear to influence the participants' performance, as indicated by their steady state times.

There is a trend in the rate of verbalization across trials, as shown in Figure 3.19. The participants appear to verbalize less during the later verbal protocol trials. This trend appears particularly dramatic for participants in the P group. During the last several trials TL and WL said almost nothing, although TL particularly had been among the most

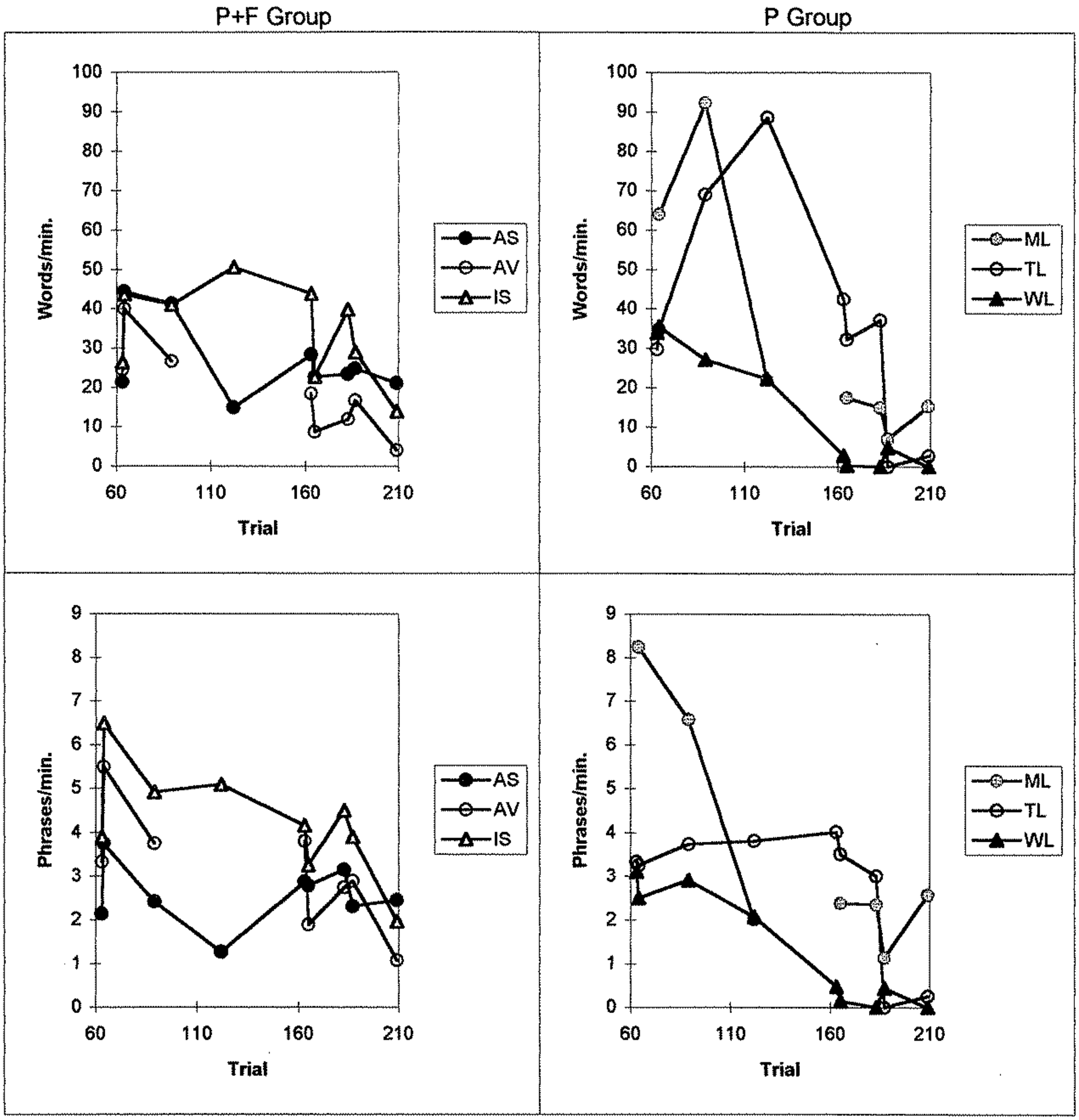

Figure 3.19 *Amount of verbalization per minute versus trial number for P+F group (left) and P group (right).*

verbal participants on earlier trials. The mean amount of verbalization was significantly different between the earlier (Trials 63, 64, 89, 122) and later trials (Trials 163, 165, 183, 187, and 209), for both interface groups when measured in *words* ($t(24) = 2.76, p < 0.05$, and $t(23) = 4.03, p < 0.01$ for the P+F and P groups, respectively). The difference between earlier and later blocks of trials, as measured in *phrases*, was only significantly different for the P group ($t(24) = 1.95$, *n.s.*, and $t(23) = 3.44, p < 0.01$ for the P+F and P groups respectively).

3.2.2 Strategies

The verbal protocols provide an additional window on the strategies that the participants used to operate DURESS II, allowing a comparison of the participants' behavior and their accompanying verbal descriptions. This section will focus on evidence of individuals' adaptation to the goal relevant constraints in DURESS II, and evidence of any more general strategies such as a rigid proceduralized approach, or trial and error strategies. (Refer to Christoffersen et al., 1994 for a parallel analysis of the participants' control recipes. Note that the verbal protocols provide an on-line description, whereas the control recipes were post hoc.) Statistical analyses were not completed due to the small sample sizes.

Adaptation. As mentioned earlier, individuals may use fewer valves to control the system when the demands for each reservoir are at or below 10 (refer to section 3.1.1 for further details). The demand for reservoir 2 (D2) exceeded 10 for only two of the verbal protocol trials: D2 was 16 in Trial 64, and 11 in Trial 89. The number of phrases referring to a valve minimization strategy are indicated in Table 3.31.

Table 3.31 *Number of References to a Valve Minimization Strategy*

		Trial									
Group	**Subject**	**63**	**64**	**89**	**122**	**163**	**165**	**183**	**187**	**209**	**Total**
P+F	as	0	0	0	0	0	0	0	0	0	0
	av	0	1	0	-	0	0	0	0	0	1
	is	1	1	0	0	0	0	0	0	0	2
P	ml	-	0	0	0	-	0	0	0	0	0
	tl	0	1	0	1	0	0	0	0	0	2
	wl	0	0	0	0	0	0	0	0	0	0
P+F											3
P											2

Each of the three participants whose *behavior* indicated a valve minimization strategy (AV, IS, and TL) also mentioned the "high" demand (above 10) in Trial 64 (refer to section 3.1.1 for a description of participants' mass input strategies). This indicates that the high demand was particularly salient for those participants who needed to change their strategy to accommodate it. Further, IS and TL explicitly mentioned a valve minimization strategy in two other instances. In Trial 122, TL said that "in pump B we're trying to use that to fill ... reservoir 2 ... pump A we're trying to fill reservoir 1." In Trial 63, IS stated the conditions for using valve VA2, "ok this one's above 10 so I'm going to have to use VA2." The results were similar for both interface groups.

Three of the participants (IS, ML, TL) discovered that the heater settings can be expressed as a simple ratio of the corresponding reservoir demand (refer to section 3.1.5 and Christoffersen et al., 1994). However, as shown in Table 3.32, only one of the participants explicitly mentioned this relationship in the verbal protocol trials examined. TL described his *rule of thumb* in 10 separate instances. For example in Trial 63, TL stated that the "steady state heater setting for reservoir 2 is about 1/3 the output and for reservoir 1 is about the same as the output." Due to TL's contributions, the P group overall made more references to heater settings as a ratio of reservoir demands than the P+F group.

Table 3.32 *Number of Steady State Heater Setting as a Ratio of Reservoir Demand*

		Trial									
Group	**Subject**	**63**	**64**	**89**	**122**	**163**	**165**	**183**	**187**	**209**	**Total**
P+F	as	0	0	0	0	0	0	0	0	0	0
	av	0	0	0	-	0	0	0	0	0	0
	is	0	0	0	0	0	0	0	0	0	0
P	ml	-	0	0	0	-	0	0	0	0	0
	tl	2	1	1	1	1	2	2	0	0	10
	wl	0	0	0	0	0	0	0	0	0	0
P+F											0
P											10

Participants may also become adapted to the perceptual features of their interface. This is revealed in statements referring to items such as the *green mark, red line,* and *vertical line*. As shown in Table 3.33, these types of remarks were confined to members of the P+F group. AS included eight such statements, while IS mentioned perceptual features twice during the earlier verbal protocol trials. This unbalanced distribution is not unexpected, since the P+F interface contains a larger number of goal relevant perceptual features than the P interface.

Table 3.33 *Number of References to Perceptual Features of the Interface*

		Trial									
Group	**Subject**	**63**	**64**	**89**	**122**	**163**	**165**	**183**	**187**	**209**	**Total**
P+F	as	0	0	4	1	2	0	0	1	0	8
	av	0	0	0	-	0	0	0	0	0	0
	is	1	0	1	0	0	0	0	0	0	2
P	ml	-	0	0	0	-	0	0	0	0	0
	tl	0	0	0	0	0	0	0	0	0	0
	wl	0	0	0	0	0	0	0	0	0	0
P+F											10
P											0

General Strategies. Participants may operate DURESS II using a number of overall strategies. These may be divided into three classes: rigid procedures, flexible goal-oriented strategies, or simply trial and error. Standardized operating procedures were revealed in descriptions of strategies using such words *always, normal, usual,* and *standard.* Table 3.34 lists the number of phrases that fall into this category for each participant. Individuals in the P group were more likely to indicate standardized operating procedures than individuals in the P+F group. This conforms with observations derived from the complexity of the action transition graphs (section 3.1.1).

Table 3.34 *Number of References to Standardized Operating Procedures*

		Trial									
Group	**Subject**	**63**	**64**	**89**	**122**	**163**	**165**	**183**	**187**	**209**	**Total**
P+F	as	0	0	0	0	0	0	0	0	0	0
	av	0	0	0	-	0	0	0	0	0	0
	is	0	0	0	0	1	0	0	0	1	2
P	ml	-	1	0	0	-	0	1	0	1	3
	tl	1	1	1	1	0	1	0	0	0	5
	wl	0	0	0	0	0	0	0	0	0	0
P+F											2
P											8

Another measure reflecting standardized operating procedures is the extent to which individuals mentioned precise quantitative component settings or reservoir levels. Participants using rigid procedures tend to set components to pre-specified values, use numerical levels as cues, or use quantitative calculations to determine settings. Table 3.35 outlines the number of references to precise quantitative values for each participant. Only phrases containing explicit numerical values were included in these totals. References to *maximum, minimum, on, off, full, increase, decrease*, etc. were not included (conforming to the coding definition used by Christoffersen et al., 1994). The total number of references to precise quantitative values was higher for the P group than the P+F group, agreeing with the analysis of the participants' references to standardized operating procedures.

Table 3.35 *Number of References to Precise Quantitative Values*

Group	Subject	Trial 63	64	89	122	163	165	183	187	209	Total
P+F	as	1	0	3	0	0	1	0	0	0	5
	av	0	0	0	-	1	0	0	0	0	1
	is	5	0	3	4	4	4	4	4	3	31
P	ml	-	11	14	4	-	6	2	2	2	41
	tl	0	0	6	4	7	4	4	0	0	25
	wl	5	5	4	3	2	0	0	0	0	19
P+F											37
P											85

Note that TL, the best individual in the P group, had both a high number of statements referring to standardized operating procedures, and to precise quantitative values. Further, he consistently used a rule of thumb to determine the heater settings (as described in the Adaptation subsection). In contrast AV, the best individual in the P+F group, never referred to standardized operating procedures, only mentioned one quantitative value, and did not employ a precise rule to determine the heater settings. This suggests that the strategies that are most successful while using the P interface differ from those that are most successful while using the P+F interface.

Another type of overall strategy involves simply guessing what the correct component settings should be and then iterating until the system becomes stable. This is referred to as a trial and error strategy. Table 3.36 shows the number of references that participants made to a trial and error strategy. Phrases were counted if they included references such as *guess, let's try, let's see, fiddle, may be appropriate, adjust until.* Participants in the P group were more likely to mention a trial and error strategy than participants in the P+F group. Further, the worst participants in each group (in terms of completion times) mentioned using a trial and error strategy, whereas the best participants in each group (AV, IS, and TL) made no such references.

Table 3.36 *Number of References to Trial and Error Strategy*

		Trial									
Group	**Subject**	**63**	**64**	**89**	**122**	**163**	**165**	**183**	**187**	**209**	**Total**
P+F	as	1	0	0	0	0	0	1	0	0	2
	av	0	0	0	-	0	0	0	0	0	0
	is	0	0	0	0	0	0	0	0	0	0
P	ml	-	1	3	0	-	0	2	0	0	6
	tl	0	0	0	0	0	0	0	0	0	0
	wl	2	2	1	1	0	0	0	1	0	7
P+F											2
P											13

3.2.3 Metacognition

Although metacognition is a popular and widely used concept, it is both difficult and contentious to determine which specific statements should be classified as metacognitive. This study examines three main types of statements that may be considered metacognitive: metastrategies, self-monitoring, and predictions. While coding statements as metacognitive, attention was paid to the *purposes* of the statements. A cognitive strategy is concerned with reaching a goal, whereas a metacognitive strategy (or metastrategy) evaluates issues such as the individual's confidence that the goal has been reached, or the ease with which the goal was reached (Flavell, 1987).

Metastrategies. Metastrategies are rules that are used to evaluate other rules (Chi, 1987). Statements were coded as metastrategic if two criteria were met: participants gave a reason for using a particular strategy, and the reason fell into categories similar to those outlined by Carr et al. (1994). These include reasons that "referred to strategy ease, task difficulty, the reliability of the strategy, the availability of visual cues provided by the strategy, or the utility of the strategy for later learning" (Carr et al., 1994, p. 587). In addition, reasons referring to strategy speed were also coded as metacognitive since, although achieving faster trial times is not an explicit system goal, this was a major determinant of the strategies that the participants chose.

The total number of phrases that explained or justified control actions are included in Table 3.37. There was very little difference between interface groups in the number of statements giving reasons for control actions. Further, the most proficient participant in the P+F group (AV) provided the fewest explanations or justifications, whereas the least proficient participant in the P+F group (AS) provided many more explanations and justifications. Thus, there does not appear to be a relationship between the number of explanatory statements and performance in the P+F group. In contrast, the best participant in the P group (TL) gave the most explanations overall. However, the number of statements that TL gave which explained or justified his control actions dropped off rapidly in the later trials. (This corresponds to a similar decrease of explanations in TL's control recipes, Christoffersen et al., 1994.)

Table 3.37 *Number of Statements Explaining or Justifying Control Actions*

		Trial									
Group	**Subject**	**63**	**64**	**89**	**122**	**163**	**165**	**183**	**187**	**209**	**Total**
P+F	as	4	4	8	1	6	2	2	6	2	35
	av	0	0	1	-	1	0	1	0	0	3
	is	4	3	9	9	6	1	6	2	1	41
P	ml	-	3	6	1	-	0	2	0	0	9
	tl	5	3	14	16	11	3	6	0	0	58
	wl	5	1	3	3	0	0	0	2	0	14
P+F											79
P											81

Only a fraction of the explanations given in Table 3.37 could be described as metastrategic. The number of metastrategic phrases uttered by each participant in each of the verbal protocol trials are listed in Table 3.38. Some participants (AV and ML) did not utter any metastrategic statements at all. The majority of the remaining participants referred to only 3 or 4 metastrategies over the course of nine verbal protocol trials. Again, TL was exceptional in this regard; he included a total of 13 metastrategic statements. However, participants in each interface group included a similar number of metastrategic statements.

Table 3.38 *Number of Metastrategic Phrases*

		Trial									
Group	**Subject**	**63**	**64**	**89**	**122**	**163**	**165**	**183**	**187**	**209**	**Total**
P+F	as	1	0	2	0	0	0	0	0	0	3
	av	0	0	0	-	0	0	0	0	0	0
	is	1	0	1	2	0	0	0	0	0	4
P	ml	-	0	0	0	-	0	0	0	0	0
	tl	1	0	5	3	2	0	2	0	0	13
	wl	1	1	1	0	0	0	0	0	0	3
P+F											7
P											16

Self-monitoring. Self-monitoring statements include the participant's general evaluations of their performance. These phrases often include words such as *good, bad, fast, going well, fine,* etc. This coding category is similar to the *checking* sub-category of *problem management*, as described by Lawson and Chinnappan (1994), or the *monitoring* classification described by Chi et al. (1989). In both of these studies, good students were better able to accurately monitor their degree of progress or comprehension than poor students. Table 3.39 summarizes the number of self-monitoring statements for each participant. AV and IS had the largest number of self-monitoring statements. These individuals also had the fastest steady state times in the P+F group. In the P group, only ML included a number of self-monitoring phrases similar to the best P+F participants. Suggestively, ML also had the best performance when he transferred to the P+F interface (Christoffersen et al., 1994). There was very little difference between interface groups in the number of self-monitoring statements.

Table 3.39 *Number of Self-Monitoring Phrases*

		Trial									
Group	**Subject**	**63**	**64**	**89**	**122**	**163**	**165**	**183**	**187**	**209**	**Total**
P+F	as	0	0	0	0	0	0	0	0	0	0
	av	1	3	3	-	2	2	0	2	0	13
	is	1	0	0	2	1	1	3	6	2	16
P	ml	-	1	6	2	-	3	0	0	1	12
	tl	1	0	1	1	4	0	0	0	1	8
	wl	2	1	1	0	0	0	0	0	0	4
P+F											29
P											24

Predictions. Predictions include indications of when the individuals expected the start-up phase of a normal trial to end. The output flow goals (demands) change after the system has been in the goal regions for five consecutive minutes (steady state). Thus, in order to accurately predict when the demands will change, the participants had to monitor the system to determine when the goals were reached and how much time had elapsed since that point. Table 3.40 exhibits the number of predictions. Again, there was little difference in the total number of predictions made by each interface group. However, the most successful individuals in the P+F group (AV and IS) also made the largest number of predictions.

Table 3.40 *Number of Predictions of End of Start-up*

		Trial									
Group	**Subject**	**63**	**64**	**89**	**122**	**163**	**165**	**183**	**187**	**209**	**Total**
P+F	as	1	0	0	0	0	0	0	0	0	1
	av	2	0	1	-	0	0	0	1	0	4
	is	0	0	0	1	1	0	1	2	1	6
P	ml	-	0	1	1	-	1	0	0	0	3
	tl	0	0	0	1	0	1	1	0	0	3
	wl	0	0	0	0	0	0	0	0	0	0
P+F											11
P											6

Most of the predictions stated that the demands would change after a given interval of time. Since these statements themselves spanned a period of time, it is difficult to determine precise values to characterize the accuracy. However, most of these interval time estimates were correct within roughly 30 seconds. The cases where precise quantitative predictions were provided are summarized in Table 3.41. AV and TL, the best participants in their respective groups, were impressively accurate. These participants could predict the time that the demands would change to within 3 seconds of the actual time, showing very tight coupling to the system state. IS was the only other participant who ventured precise time estimates. He predicted the times to within 30 seconds, with the exception of one time estimate which he later revised due to an error he made in controlling the system.

Table 3.41 *Prediction Accuracy for Precise Quantitative Predictions*

Group	Subject	Predicted	Actual	Error
P+F	av	5:53	5:51	0:02
	is	6:45	6:21	-0:24
	is	6:45	7:38	-0:53
	is	7:30	7:38	-0:08
P	tl	5:45	5:44	0:01
	tl	5:45	5:42	0:03

3.3 Cognitive Learning Styles

3.3.1 Study Process Questionnaire

There are three main approaches to learning that are revealed by Bigg's (1987) Study Process Questionnaire (SPQ): deep, achieving, and surface. These approaches to learning are composed of strategy and motive combinations, which capture the role of personality and the situation, respectively. The SPQ results in six motive and strategy scores than can be combined to produce three approach scores. The highest score determines the participants' approach to learning for this analysis. These results are outlined in Table 3.42. The participants from a second related study (JAERI II, Hunter, 1995) are also included in this analysis.

Table 3.42 *Participants' Approaches to Learning*

Group	Subject	SPQ Result	Prior Assessment
JAERI I P+F	as	Deep	Surface
	av	*Deep*	*Deep*
	is	-	Achieving
JAERI I P	ml	Deep	Surface
	tl	*Achieving*	*Achieving*
	wl	Achieving	Deep
JAERI II P+F	JR	Deep	Surface
	CD	*Deep*	*Deep*
	DC	*Deep*	*Deep*
	MI	Achieving	Surface
	JS	Achieving	Deep
	LG	Achieving	Surface
	PC	Achieving	Surface
	RM	*Achieving*	*Achieving*
JAERI II P	JN	Deep	Achieving
	SR	Achieving	Surface
	LT	*Surface*	*Surface*
	EP	Deep	Achieving
	KL	*Deep*	*Deep*
	PY	*Surface*	*Surface*
	NZ	*Deep*	*Deep*
	FP	Deep	Achieving

Note: SPQ results that agree with the prior assessment are indicated by italics.

The subjective assessments of the previous experimenters do not conform with the results from the SPQ at a greater than chance level. However, the two assessments concurred most frequently when the participants were expected to have a deep approach to learning (5 out of 7). An intermediate number of assessments concurred when considering an achieving approach (2 out of 5), and the fewest agreed when the participants were expected to have a surface approach (2 out of 9). It is possible that the participants felt that a deep approach to learning was more desirable than a surface approach, causing them to bias their answers in this direction. The distribution of scores conforms with this interpretation. As shown in Table 3.43, there were differences between the number of participants reporting high scores in each of the approach categories. Most participants (86%) scored in the 8th decile and above in either deep motive, deep strategy, or both. In contrast, only 33% of the participants received high scores in at least one of the surface categories. Thus, these results may not be representative of the participants' actual approaches to learning. Alternatively, most of the participants may truly be inclined towards a deep approach but their behavior in the context of DURESS II does not reflect this orientation.

Table 3.43. *Distribution of High Scores in SPQ*

Approach	Number of participants	
	8th decile or higher	**Below 8th decile**
Deep	18	3
Achieving	13	8
Surface	7	14

The participants' scores were correlated with the steady state times for the final 10 normal trials (for JAERI II), in order to determine whether the participants' learning approaches influenced performance on either or both of the interfaces.[2] An achieving strategy was positively correlated with time for the P+F subjects ($r(6)=0.72, p < 0.05$), while a deep approach was positively correlated with time overall ($r(14)=0.50, p < 0.05$). This results in the paradoxical situation that those participants expressing the strongest desire to succeed, in fact achieved the worst results in terms of steady state trial times. However, no clear conclusions can be derived from these measures since they are confounded both with possible distortions of the participants' scores, as discussed above, and an unequal distribution of learning styles across interface groups and treatment groups. Similarly, no firm conclusions can be drawn from a correlation between SPQ scores and fault detection, diagnosis, and compensation measures.

3.3.2 Spy Ring History Test

The Spy Ring History test examines the extent to which a participant adopts a holist or serialist approach to learning several communication networks (refer to Appendix A for further details). Serialists prefer questions requiring direct reproduction of the communication links, and holists prefer questions requiring a higher level

[2]Only the JAERI II participants are included in this analysis. The steady state trial times for the participants in the main study (JAERI I) were lower due to their greater experience operating DURESS. The JAERI II participants only completed 67 trials, while the JAERI I participants completed 224 trials. The sample size is too small to conduct a similar analysis with the JAERI I participants.

integration of information. Versatile learners are able to adopt either a holist or a serialist approach as the need arises. The Spy Ring History test results in percentage scores for holist and serialist questions (neutral questions that favor neither the holist nor the serialist are also included). The highest percentage indicates the participants' cognitive style. If the holist and serialist scores were within 10% of each other, the learner was operationally defined as versatile. The results for the 21 participants (including the JAERI II subjects) are listed in Table 3.44.

Table 3.44 *Classifications from Spy Ring History Test*

			Spy Ring Scores	
Group	**Subject**	**Classification**	***Holist***	***Serialist***
JAERI I P+F	as	Serialist	29%	**57%**
	av	Versatile	64	69
	is	-	-	-
JAERI I P	ml	Holist	**79**	56
	tl	Versatile	29	27
	wl	Versatile	71	64
JAERI II P+F	JR	Serialist	21	**33**
	CD	Holist	**86**	64
	DC	Versatile	86	86
	MI	Serialist	21	**56**
	JS	Serialist	79	**94**
	LG	Serialist	71	**89**
	PC	Serialist	71	**87**
	RM	Versatile	71	67
JAERI II P	JN	Serialist	64	**94**
	SR	Versatile	86	88
	LT	Serialist	36	**73**
	EP	Holist	**71**	58
	KL	Versatile	71	76
	PY	Serialist	50	**90**
	NZ	Serialist	29	**62**
	FP	Versatile	71	71

Note. The highest scores are indicated by bold, with the exception of cases in which these values differ by less than 10%.

Notice that fortuitously the participants are balanced across interfaces according to holism-serialism for JAERI II[3]. This allows us to conduct further analyses of the

[3]See footnote 2.

relationship between this cognitive style and performance. The holist and serialist scores were correlated with performance for both normal and fault trials. None of the correlations between serialist scores and performance reached significance. However, there were significant correlations between holist scores and performance. These results are shown in Table 3.45. Pask (1976) mentioned that "provided that the overall and neutral scores are high enough ... it is possible to distinguish stylistic tendencies" from the Spy Ring History Test (p. 148). For this reason, a cut-off was operationally set at 40%. All participants with overall scores below this value were excluded from further analyses.

Table 3.45. *Correlations Between Holism Scores and Performance*

	Correlation		
	JAERI II	**P+F**	**P**
Normal Trial Time	-0.43	-0.90 **	-0.09
Detection Time	-0.56 *	-0.97 **	-0.14
Diagnosis Accuracy	0.53 *	0.86 *	-0.09
Compensation Time	-0.50 *	-0.90 **	0.13

Note. Participants scoring below 40% (N=1) are not included in this analysis.

df = 13 for JAERI II, df = 5 for P+F group, and df = 6 for P group.

* $p < 0.05$, ** $p < 0.01$

Clearly, those participants that achieved higher scores in holism performed better when using the P+F interface. However, there is no significant relationship between holism and performance for participants using the P interface. In the P+F group, the higher the participants' holist score, (1) the faster they completed normal trials, (2) the faster they detected a fault, (3) the more accurately they diagnosed a fault, and (4) the faster they compensated for a fault and returned the system to steady state. (For a detailed discussion of the derivation of detect times, diagnosis scores, and compensation times, refer to Christoffersen et al., 1994b; Hunter, 1995). The contribution of the P+F interface participants is reflected in the correlations between holism and fault performance overall for JAERI II.

Generally, subjects that achieved higher overall scores on the Spy Ring History test also demonstrated better performance on normal and fault trials. However, this relationship only reached significance for fault detection ($r(13) = -0.61, p < 0.05$ for

JAERI II, and $r(5) = -0.86$, $p < 0.05$ for P+F interface). Whether holism is related to ability more generally is a question that could merit further investigation. Studies involving other members of this family of styles have shown correlations with ability (field dependence-independence: Messick, 1994; Eysenck, 1994; impulsivity-reflectivity: Morris & Rouse, 1985; Rouse & Rouse, 1982).

As discussed in Section 1.2.3, matching teaching style to learning style allows individuals to learn more effectively (Pask & Scott, 1972; Pask, 1976). These results indicate that the P+F interface may provide a better match to the holist learning style. Holists may more effectively use the relationships between variables that are made explicit in the P+F interface. Further, the perceptual cues in the P+F interface can support the holists' tendencies to react based on the current situation rather than following standardized operating procedures (Howie, 1995).

4. DISCUSSION

This thesis examined the cognition of participants as they learned to operate the DURESS II simulation with either a traditional (P) interface or an ecological (P+F) interface over an extended period of time. The participants' increasing expertise and adaptation to the system constraints was investigated, with an emphasis on the role of individual differences in this development. Specifically, the following three main issues were examined.

- the start-up strategies used by the participants and any effects of experience and interface type on these strategies
- the frequency of participants' metacognitive statements and any interaction between metacognition, interface type, and performance
- any interaction between interface type, individual participants' cognitive learning styles, and their performance.

The discussion of the results will follow this general structure.

4.1 The Effect of Experience on Strategies

4.1.1 Measures of Expertise

In previous investigations using DURESS II, steady state times were used as the principal performance measure for normal trials (Pawlak, 1994; Christoffersen et al., 1994b; Hunter, 1995). Generally, as the participants gained more experience, they achieved faster and more consistent steady state times. In this study, several additional measures were shown to reveal the participants' increasing expertise. These results are outlined below.

Action transition graph complexity. Generally, the participants' action transition graphs became less complex with experience, indicating an increasingly systematic approach to operating DURESS II. This agrees with the findings of Moray et al. (1986).

Path length in state space. The mean path lengths in the state space of temperature versus demand also decreased with experience. This indicated that the participants approached the goals in the state space more directly with experience. In addition, the area under graphs of the total distance to the goals versus time decreased with experience. Note that, even with extensive experience, the participants did not take the shortest path through the state space toward the goals. The participants first reached the temperature goal and then the outflow demand goal.

Deviation from temperature goal line in mass versus energy inventory graph. In graphs of mass inventory versus energy inventory, the deviation of the participants' paths from the temperature goal line decreased with experience. Further, the closeness of fit to the goal line seemed to indicate the participants' relative expertise. When the ratio of energy inventory to mass inventory was plotted against time, it showed that the participants reached the temperature goals more quickly with increasing experience.

Proportion of early control actions on timeline. Timelines revealed that, with increasing expertise, the participants made a larger proportion of their control actions near the beginning of each trial. This reflects feedforward control, as discussed in Moray et al. (1986).

These performance measures provide a way of examining participants' behavior in detail. They allow a quantitative evaluation of the participants' control strategies and their relative expertise. These measures may be useful in evaluating performance in future studies involving DURESS II.

4.1.2 Evidence of Adaptation

The participants showed increasing adaptation to the goal relevant constraints in DURESS II as they gained more experience operating the system. The clustering of the best participants' control actions changed with experience. Most participants initially controlled the components in sequences based on their physical attributes (pumps, heaters, valves). However, TL and AV, the most proficient participants in each interface group, adopted a more functional approach with experience. Their control actions were more closely grouped according to which reservoir(s) a component would affect.

One of the most important structural constraints in DURESS II is the redundant nature of the two feedwater streams when neither demand is above 10 units/s. Three of the six participants (AV, IS, and TL) took advantage of this constraint by adopting a valve minimization strategy. While using this strategy, the participants kept valves VB1 and VA2 closed whenever possible, creating a one-to-one mapping between the feedwater streams and reservoirs. These participants became increasingly sensitive to the conditions under which the valve minimization strategy could be used. They matched the valve configuration to the demand goals almost flawlessly during the final block of trials. The participants' verbal protocols confirmed that they were consciously aware of this strategy. Further, this strategy was correlated with faster steady state times and less variable performance.

A second important constraint is the relationship between the steady state heater setting and the outflow demand goal for each reservoir. The setting for HTR1 should be the same as the numerical value of D1, and the setting for HTR2 should be one third of the numerical value of D2. Three of the six participants (IS, ML, and TL) expressed the heater setting as a ratio of reservoir demand (Christoffersen et al., 1994b). During the final block of trials, these participants made significantly fewer heater control actions than participants who adopted an alternative heater control strategy. However, TL was the only participant to explicitly mention the relationship between heater setting and reservoir demand in his verbal protocols.

Thus, as hypothesized, the participants demonstrated adaptation to the goal relevant constraints within DURESS II with increasing experience. Further, the better participants showed evidence of greater adaptation. There is additional evidence of differential adaptation between the two interface groups that will be discussed in the following section.

4.2 The Effect of Interface on Strategies

In the previous sections, evidence of increasing expertise was presented for subjects in both the P+F and P groups. However, not all of the findings apply to both of the interface groups equally. For instance, participants in the P+F group were more likely to maintain high mass inventories than participants in the P group. With high mass inventories, the energy goal region is broader, making the system easier to control (Pawlak, 1994). This suggests that the P+F group members adapted to this goal relevant constraint because it is visible in the energy balance graphic in their interface. However, since analogous information was not visible in the P interface, the P participants did not adapt to this aspect of DURESS II.

In general, the P+F interface contains a larger number of goal relevant perceptual features than the P interface. Thus, it is not surprising that participants in the P+F group made substantially more references to the perceptual features of the interface than participants in the P group. This indicates that the participants in the P+F group adapted to the perceptual features of their interface. However, reliance on the perceptual features of the P+F interface is not a substitute for deeper knowledge of the system. The subject who made the most references to the perceptual features of the P+F interface, AS, was also the least competent P+F group member according to most measures. It appeared that AS relied on the surface features of the P+F interface without deeper understanding of the system since he showed little evidence of adapting to the other goal relevant constraints of the system.

There is also evidence for differences in more general operating strategies across interfaces. This is revealed in an analysis of the action transition graph complexity. There was no significant correlation between action transition graph complexity and performance (steady state times) for experienced participants in the P+F group. However, there was a significant positive correlation between complexity and this measure of performance for the P group. If action transition graph complexity is considered as a measure of "procedural variety", a simple action transition graph may indicate standardized operating procedures. Thus, these results may indicate that rigid procedural strategies are associated with successful performance for the P group but not for the P+F group.

This analysis is consistent with findings from the verbal protocols. Participants in the P group were marginally more likely to mention the use of standardized operating procedures than participants in the P+F group. The most successful participant in the P group (TL) made the largest number of these statements. Participants in the P group also made more references to precise, quantitative component settings or reservoir levels. Often these quantitative values were used as conditions for action during operation (for example, trying to maintain the reservoir level at around 50 units).

These findings provide some support for the hypothesis that participants effectively using the P interface will exhibit mainly rigid, procedural strategies. There is less evidence to support the assertion that participants effectively using the P+F interface will exhibit more flexible, goal-oriented strategies based on a functional understanding of the system. An information theory analysis was attempted to try to provide a more direct indication of the degree of proceduralization, but this analysis did not provide any clear results.

4.3 The Role of Metacognition

Overall, the participants made very few statements that could be categorized as metacognitive. Further, there was very few differences between the interface groups in terms of the number of metastrategic phrases, self-monitoring phrases, or predictions. Thus, it appears that neither interface alone provides a medium for promoting reflection as expressed in the verbal protocols. Yet there were differences in how often the participants reflected on their performance and strategies. These results were derived only from an analysis of normal trials during start-up. The first recorded verbal protocol occurs on Trial 63, when the start-up procedure has probably become quite routine for the participants, providing little motivation for reflection. A different conclusion might be reached from an analysis of the fault trials. The abstraction hierarchy representation present in the P+F interface provides support for knowledge based behavior, especially in the case of unfamiliar, unanticipated situations. Thus, participants using the P+F interface might be expected to include more metacognitive statements in their verbal protocols for fault trials.

Although there was no significant difference in the number of metacognitive statements across interfaces, there were individual differences. Generally, participants expressing a larger number of metacognitive statements also exhibited better performance. TL, the most competent participant in the P group, made the highest total number of metastrategic statements -- over three times as many as any other participant. Further, the most successful participants in the P+F group, AV and IS, made the most self-monitoring statements and predictions. In the case of precise numeric predictions, the most successful participants in each group (AV and TL) were the most accurate. However, due to the small number of participants in the study, these results are more suggestive than definitive.

4.4 The Role of Individual Differences

Previous studies involving DURESS II have noted that there are large individual differences in performance that seem related to individual learning attitudes and/or motivation (Christoffersen et al., 1994; Hunter, 1995). It is important to try to identify and control for these variables.

The SPQ did not differentiate among the participants. Subjective assessments of the participants' approaches to learning by previous experimenters did not conform with the results from the SPQ at a greater than chance level. This may be partly due to the participants' apparent bias to describe themselves as deep. Most of the participants (86%) scored in the 8th decile and above in at least one of the deep subscales. In contrast, only 33% of the participants received high scores in at least one of the surface subscales. Moore et al. (1994) had similar difficulties using the SPQ to tap experienced pilots approaches to learning. As a result, Moore et al. (1994) developed the Pilot Learning Processes Questionnaire (PLPQ), a modified version of the SPQ designed to reflect the specific context of pilot training. It might be necessary to undertake a similar modification of the SPQ in order to make it more applicable to the DURESS II environment.

The Spy Ring History Test more clearly differentiated among the participants' performance on the P+F interface. The P+F participants with the highest holist scores achieved faster normal trial times. They were able to detect more quickly that a fault had occurred, and provided more complete diagnoses of the nature of any faults. They were also able to compensate for the faults and return the system to steady state within a shorter period of time. Note, however, that there was no apparent relationship between holism and performance for participants using the P interface. This suggests that the P+F interface provides a better match to a holist learning style than the P interface. Thus, measures of holism-serialism may provide a useful tool for future studies involving the evaluation and implementation of ecological interface designs.

4.5 Implications

1. The performance measures developed in this study can be used as indicators of adaptation in future studies. These measures could provide a basis for developing

more comprehensive measures of adaptation for use in actual or simulated process control environments.

2. Operators effectively using a traditional (P) interface appear to rely on standardized procedures more than operators effectively using an ecological (P+F) interface.
3. To enhance their performance, operators should critically reflect upon the reasons for using strategies, and monitor their performance.
4. To fully realize the benefits of P+F, operators should possess a more holistic cognitive style. If this finding can be generalized to a larger sample, it may have implications for the selection of operators.

4.6 Limitations

DURESS II allows a comparatively naturalistic approach to experimentation, providing rich, detailed information about the behavior of individuals. By incorporating many of the elements of a complex system, the results may be more applicable to industrial plants. However, in order to provide this more naturalistic setting, there is a corresponding loss in experimental control. Thus, the cause and effect relationships are no longer as clear as in a traditional laboratory experiment. Meaningful conclusions are most likely to become evident using multiple, converging measures, and through an individual analysis of each participant's data.

Further, the small sample size used in this thesis may limit the generalizability of the results. However, the duration and complexity of this experiment precluded the use of larger groups. This limitation was partially offset by the large number of trials. This allowed an unprecedented opportunity to look at the acquisition of experience under conditions more representative of the daily operating environment in process control systems.

Some of the statistical tests in this thesis treat each observation as if it were a participant. This approach allows a greater number of degrees of freedom, however, it limits the generalizability of the conclusions. These tests allow generalization to a population of trials in which the six participants are taken as fixed. Thus, the statistical confidence level applies to the conclusion that the same six participants would continue to exhibit a similar pattern of behavior. This type of generalizability is most useful in practical applications, for example, distinguishing between operators based on their past performance (C. Bereiter, personal communication, December 18, 1995).

Finally, verbal protocols may not be a perfectly reliable source of data since the participants did not always verbalize their thoughts. Thus, the verbal protocols provide only an incomplete picture of the participants' cognition. In addition, the coding of the verbal protocols is open to personal interpretation. In order to partially compensate for this factor, any differences in opinion during coding were resolved through consultation with a second rater.

4.7 Future Directions

Future studies on the role of adaptation and individual differences in interface design for complex systems could investigate a number of related questions:

1. Do the performance measures developed in this study reveal similar patterns of adaptation when applied to other data sets? Which are the most sensitive indicators of the level of adaptation or expertise?
2. What are appropriate measures of flexibility versus procedural control?
3. What are appropriate measures of the degree of coupling between participants' actions and the system state?
4. Do participants' verbal protocols include more metacognitive statements during fault trials than during normal trials? Do participants using P+F interface include more metacognitive statements in their verbal protocols from fault trials than participants using a P interface?
5. Does requiring participants to be more reflective affect their performance? (A study of the influence of self-explanation on performance using the P+F interface is currently in progress.)
6. Would a domain-specific version of the SPQ differentiate between the participants' approaches to learning?
7. How well does the Spy Ring History test account for participants' performance in general?

8. How do other methods of assessing holism-serialism compare to the Spy Ring History test? Is it possible to use a less labor intensive method of assessing this cognitive style (for example, the questionnaire developed by Ford, 1985)?

This study is part of a larger effort to examine the role of adaptation in interface design for complex systems. Each piece of knowledge brings us closer to the goal of providing more safe and effective interfaces for process control. Understanding the role of individual differences is an important step towards this goal.

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6. APPENDICES

6.1 Appendix A - Instruments for Assessing Individual Differences

6.1.1 Test for Holism-Serialism

The 'Spy Ring History' test is based on learning lists of ordered pairs that represent the names of spies and their connections (Pask, 1976). The spies may only communicate to spies with which they have a connection in the network. The spy networks may be visualized as graphs with spies at the nodes and links showing who may communicate with whom. There are five networks representing the spy connections in the years 1880, 1885, 1890, 1895, and 1900. While the spy names remain constant over this period, there are some regular changes in the organizations.

The participants must memorize the lists of associated pairs faultlessly. After they have learned the lists, they answer questions about the history. The patterns of answers reveal two different ways of learning. Comprehension learners (holists) can answer questions involving synthesis or prediction, such as:

"Which agent or agents in 1880 were the most important for the integrity of the organization?"

"What do you suppose happened politically between 1880 and 1900?"

Operation learners (serialists) can answer questions that focus on particular networks or lists of associated pairs, such as:

"State the names of the three countries and the code names of agents resident in each country?"

"Write out the list for 1890"

The answers are scored for comprehension and operation learning styles; in addition there is a score derived from the answers to neutral questions. When the lists are learned well enough to provide a sufficient number of correct answers, the cognitive style tendencies of the individuals may be identified.

6.1.2 Test for Approaches to Learning

The Study Processes Questionnaire (SPQ) instrument contains 42 items. Individuals indicate their agreement with items on a five point Likert scale (from 1 = strongly disagree to 5 = strongly agree). The questionnaire contains items from the subscales in the following order: surface motivation, deep motivation, achieving motivation, surface strategy, deep strategy, and achieving strategy. Table A.1 gives a sample of these items (Biggs, 1987, p. 132-133).

Table 6.1. *Sample of SPQ Items*

Subscale	**Item**
Surface Motivation	Whether I like it or not, I can see that further education is for me a good way to get a well-paid or secure job.
Surface Strategy	I generally restrict my study to what is specifically set as I think it is unnecessary to do anything extra.
Deep Motivation	I find that at times studying gives me a feeling of deep personal satisfaction.
Deep Strategy	In reading new material I often find that I'm continually reminded of material I already know and see the latter in a new light.
Achieving Motivation	One of the most important considerations in choosing a course is whether or not I will be able to get top marks in it.
Achieving Strategy	I try to work consistently throughout the term and review regularly when the exams are close.

The SPQ is scored by taking the sum of the responses to the five point Likert items for each subscale. There are, then, a total of six subscale scores: three motive and three strategy. The approach scores are obtained by summing the corresponding motive and strategy scores. The raw scores can be converted into percentiles using the tables for the appropriate population. For the participants in this study, the relevant table describes norms for University Science Males. (Other tables give norms for University/College, Arts/Education/Science, and Male/Female students.)

6.2 Appendix B - Trial Schedule

	Output Demand Flow Rates		
Trial No.	**Reservoir 1**	**Reservoir 2**	**Description**
			Start-up only Trials
1	8	2	
2	2	7	
3	3	9	
4	7	4	
5	9	8	
6	8	7	
7	4	3	
8	2	5	
9	5	10	
10	3	6	
11	7	11	
12	5	12	
13	6	11	
14	8	8	
15	8	3	
16	5	12	
17	2	2	
18	2	4	
19	3	11	
20	8	9	
21	5	2	
22	3	6	
			Verbal Protocol Trials
63	8	6	
64	3	16	Fault at 4 minutes
89	7	11	
122	5	3	
163	4	3	
165	8	7	Fault at 9 minutes
183	6	3	Fault at 7.5 minutes
187	6	7	Fault at 8 minutes
209	5	6	Fault at 7 minutes

	Output Demand Flow Rates		
Trial No.	**Reservoir 1**	**Reservoir 2**	**Description**
			Normal Trials
196	3	4	
197	8	1	
198	5	3	
199	4	11	
200	3	15	
202	6	11	
203	8	11	
204	6	1	
205	5	2	
206	4	8	
207	7	12	
208	4	15	
210	4	4	
211	9	3	
212	9	5	
213	6	13	
214	2	9	
215	3	11	
216	8	9	
217	5	2	

6.3 Appendix C - Verbal Protocols

AS Trial #63

Time	Comment
0:30	[tape starts at 0:32]
1:00	I don't recognize any special ratio between the two [referring to the demand pairs] so I'm just going to guess and do some eyeballing during the adjustment of valves ok, this is half mark so open valves [open output valves] decreasing this [reduce valve settings from maximum]
2:30	I'm setting this to maximum so that it would reach the set point quicker [heater 1] ok, the flow rates are steady state, I'm just trying to adjust the temperature now there we go
3:30	this is not hot enough [temperature 1] ok, this one has reached steady state [reservoir 2] and I just need to put some more heat into this one [reservoir 1]
4:00	some minor adjustments down here [reservoir 2] ok
4:30	so the system has reached steady state and I'm waiting for the set points to change now there will be some minor adjustments [adjust heaters]
6:00	this is getting close to the edge so I am decreasing the heater so that will fall back to the better position [adjust heater setting 2]
7:30	ok, the set points should change any time now
8:00	ok I'm adjusting the output valves to match the set points [demand pairs change at 8:02]

AS Trial #64

Time	Comment
0:00	ok, I'm starting, turning on all the valves and turning on the pumps [turn on all valves to maximum, and pumps on]
	once I see water in the tank, just turn on the heaters
0:30	I'm just taking a look at the two set points here, it looks like this plus that is going to use up the entire scale; that means I have to put the two in full scale, I don't have to lower these two now -- or at least I think so [referring to valve settings]
	I'm going to wait 'til more water coming into the reservoirs before I start adjusting the valves
1:00	ok there we go [adjust output valves to set points]
	down
	I know this one is going to take more than that one so I lower this, and this one is going to be more than that one and I lower this [lower valve settings VB1 and VA1]
1:30	put that more [raise valve setting VA1]
2:00	ok the flow rates are now stabilized, just working on the temperature now
	there we go
	trying to adjust the temperature
3:30	ok now this one is in steady state [referring to reservoir 2]
	and so is this one [referring to reservoir 1]
	no not quite, there we go
4:00	the water level is changing, that's interesting

AS Trial #65

Time	Comment
0:00	ok again, I'm opening all the valves to maximum and I'm turning on the pumps
	once there is water in the tank, start turning on the heaters
0:30	I don't see any obvious relationship between the two settings [referring to demand pairs] here so I'm just going to do ... based on guess work
	ok I'm just waiting for more water to enter the reservoirs
1:00	ok it's about half way mark and I'm turning on the valves [referring to output valves
	I know this one's going to be lower, this one's going to be lower than the other one [referring to VA1 and VB1 with respect to VA2 and VB2]
2:00	I'm trying to get the flow rates into steady state first before I work on the temperature, otherwise I'm changing the temperature setting as well, just to maintain ... oops this is going to overflow [reservoir 1]
2:30	damn
	there, there ... [adjust valve settings]
3:30	ok the system has reached steady state now, and I'm just waiting for the set points to change
5:00	ok, it's a little bit below the set points so I'm going to increase the heater a bit just to bring it back to the middle [temperature 1 and 2]
6:00	that goes, that's too much [temperature 1 and 2]
7:00	ok the set points has changed, I'm going to adjust the output valve settings to match the set points [demand pairs change at 7:17]

AS Trial #89

Time	**Comment**
0:00	ok I'm first turning on all the valves
	turn on the pumps
	once there is water in the tanks, start turning up the heat
0:30	notice that the setting here is approximately 2/3 of this here, so I adjust the input valves accordingly [referring to demand pairs]
	this is .. I take 2/3 and this is 2/3
	once I've got almost half the tank full, I'm starting to open up the output valves
1:00	see right now both the output levels, the output flow rates are ..., the input flow rates are larger than the input flow rates so I have to decrease the initial flow rates so that both would decrease [adjust valve settings]
	I need a little bit more in here [adjust valve setting VB]
2:00	well the flow rates are at steady state now, and I am just adjusting the heaters to achieve steady state in here
2:30	ok I'm leveling off the heater because it's hitting the green mark
	I am trying to get it into a vertical line now
3:30	I'm just trying to bring this line to the middle of the green line
	ok the system is reaching ... has reached steady state, just waiting for the set points to change
4:00	doing some minor adjustments here ... to the heater
5:00	doing some minor adjustments again just to keep this red line within the green line
	one thing that I did different, starting with 1994, is that I didn't wait for the water level to reach the half point before I start adjusting the valve settings, especially the output valves. I found that this is not necessary and I don't have to waste time waiting for the water level to rise up here.
5:30	for the previous sessions, or for all the 1993 sessions, what I did is that I start adjusting the output valves and when the water level hits the mid-point which I found out that's not really necessary and that's why I stopped doing it.
7:30	ok the set points should be changing about now
	ok it has changed [demand pairs change at 7:46]

AS Trial #122

Time	Comment
3:00	[tape starts at 2:59] ok I've stabilized the flow rates, I'm just going to adjust the temperature right now
3:30	ok the system has reached steady state, I'm waiting for the set points to change
5:00	I'm doing some fine adjustments, just to keep the temperature straight
6:30	ok the set points have changed

AS Trial #163

Time	Comment
0:00	turning on all the input valves turning on both pumps once there is water in the tanks, start turning on the heaters the two set points are pretty close to each other so I know the valve settings will be close [referring to input valve settings]
0:30	start opening the output valves to the set points come on [adjusting output valve settings]
1:00	ok, decreasing the input flow rate since the two add together is still approximately less than half of the overall settings so I know each one of them would at least be just half of ... it's dropping, dropping [referring to reservoir 2 volume] start turning off the heater on this side because it is reaching the green region [reservoir 2]
1:30	so it's reservoir number one we have to continue decrease the flow rate because both of them still have the input larger than the output
2:00	ok I need to decrease this one [referring to VA2] ... to increase the other one
2:30	ok ... the system has reached steady state I'm waiting for the set points to change and doing some minor adjustments perfect
4:00	ok just waiting
5:00	I've been doing some fine adjustments just to keep the set point around the green region
6:30	ok the set point has changed [demand pairs change at 6:38]

AS Trial #165

Time	Comment
0:00	ok turning on all the input valves
	turning on the pumps
	the two set points are almost identical so I know VA1 to VB2, the ratio should be almost the same [referring to demand pair]
	once there is water in the tank, I turn on the heaters
	I'm setting the set points [adjusting output valves]
0:30	the output flow rate is almost the same, let's see if I can make them identical
	ok this is about to overheat [reservoir 2]
1:00	ok I'm dropping this to 3/4 [referring to VA and VB] and I'm dropping this to half [referring to VA1, VA2, VB1, VB2]
1:30	ok I'm increasing the heater [adjusting heater 2 setting]
2:00	the flow rates are constant now
	I'm just adjusting temperature, whoa ... [adjusting heater 1 setting]
	there we go
	come on, come on [adjusting heater settings]
2:30	ok the system has reached steady state, I'm waiting for the set points to change
	and doing some fine adjustments here and there
	there we go
	the flow rates are pretty steady so I don't have to worry about them, I just need to worry about the temperature
	a little bit
3:00	ok
7:00	ok the set points have changed [demand pairs change at 7:11]

AS Trial #183

Time	Comment
0:00	ok turning on all the input valves
	turning on both pumps
	once there is water in the tanks, start turning on the heaters
	I don't see any immediate correlation, looks like this one is 2/3 the other but it's not obvious what the actual proportion is so I'm just going to guess [referring to demand pair]
0:30	ok start adjusting the output valves to the set points
	and turning, adjusting the input valves
	come on
	holy cow! [adjusting heater 2 setting]
1:00	reservoir number 2 is overheating a little bit, not much
	ok reservoir number 2 the flow rate has been stabilized
1:30	reservoir number 1 still have to adjust
	let's see [adjusting input valves]
	there
	ok the flow rates have been stabilized, I'm working on the temperature
2:00	I'm not going to overshoot this time [referring to reservoir 1 temperature]
	yes
	ok the system has reached steady state, I'm waiting for the set points to change
	and doing some fine adjustments [adjusting heater settings]
3:00	seems to be overheating here [reservoir 2]
5:00	maybe time for special effect again, where is it?
	here [screen warps]
6:30	all right set points have changed [demand pairs change at 6:56]

AS Trial #187

Time	Comment
0:00	ok turning on all the input valves
	turning on both pumps
	the two set points look very close [referring to demand pair], so I know from both VB1 to VB2 this should be almost the same setting
	once there is water in the tank start turning on the heaters
0:30	ok I'm going to set ... open the output valves
	I'm going to set all input valves to the same setting
	decreasing the overall flow rate because both of them has an input larger than the output [adjust valve settings VA and VB]
1:00	start turning off the temperature of heater number 2 because I don't want it to overheat
	still too much water [adjust valve settings VA and VB]
	let's see
1:30	ok this one has too much [reservoir 1], this one has less [reservoir 2] so I'll increase this [valve setting VA2] so that the two will balance out
2:00	ok
	ok the system has reached distance, the system has reached steady state; I'm waiting for the set points to change
	doing some fine adjustments just to keep the settings aligned in the middle
4:00	oops this one's been dropping too much [reservoir 1 temperature]
6:30	all right the set points have changed [demand pairs change at 6:56]

AS Trial #209

Time	Comment
0:00	ok turning on all the input valves
	turning on both pumps
	once there's water in the tank I'll start turning on heater temperature
	the two set points are very close to each other [referring to demand pair] so I know that VA1 to VB2 the settings will be the same ... or very close
0:30	ok just going to let more water into the tank
	first I'm turning on all the output valves to match the set points
	and setting VA1 to VB2 to the same level
	decreasing the overall flow rate [adjust valve settings VA and VB]
1:30	getting too much water in the input
2:00	all right
	ah that's going to overshoot, reservoir 1 is going to overshoot [reservoir 1 temperature]
	don't do that!
	just make ... ok there we go
	ok
2:30	ok the system has reached steady state, waiting for the set points to change
5:30	doing some fine adjustments just to keep the temperature constant
6:30	ok the set points have changed [demand pairs change at 6:56]

AV Trial #63

Time	Comment
0:00	off we go, da da da da da
	ok, okay dokey
	we turn on all these bloody thingies ... heat
	and here we go
	and there she goes ladies and gentlemen
	welcome to our new fantastic show
0:30	the amazing heating machine
	oops, this guy went way, way, ... way up OK
	that wasn't a very good, not a good start up
1:00	come on, come on
	ok, inches 109, ok
	is not in yet? no now I see it
1:30	this guy goes too high up, down boy [referring to temperature]
	and as you can probably observe, we have reached steady state
2:00	now this will take us about 4 minutes to finish it and have those output produce changed
2:30	reduce heating up here just a little bit
	the resolution is bad as I said before and I will reiterate [referring to scales]
	you can not do fine tuning on this thing
3:00	ok, the boring stuff
5:30	oops, mistake
6:00	ok, any time now those thingy will change [referring to demand pairs]

AV Trial #64

Time	Comment
0:00	on on [turning on pumps and valves], oh oh shit, this guy has a lot of water [referring to reservoir 1]
	ok its lots and lots of waters
	here heat heat [turning on heater]
0:30	let's put some water in the thing first [turns down output valve to fill reservoir 2]
	see what's this good now
1:00	well, what what what..., ok let's go in here and what is there? [adjusting valve settings]
	oh a little bit too much water [referring to reservoir 1]
1:30	ok this is done, this is done, good beautiful
	not beautiful, this guy needs some more water, this is ... oh oh oh shit [heat getting too high in reservoir 1]
2:00	good, now water, what? again!
	how much water do we have?
	stop that shit [reservoir 2 inflow too high]
	oops, this one's low [referring to reservoir 1 temperature]
	heat, more temperature here, heat, more temperature, heat heat
2:30	reduce a little bit water here, that's ridiculous!
	oh, I don't want all that! [turn down valve settings for reservoir 1]
	fix something like that, there
3:00	but it isn't through here, ha ha ha ... You're smart, I'm smart
	there great
	it's amazing
3:30	my eyes, this thing makes my eyes hurt man, Jesus Christ
4:00	whoa whoa whoa what the hell is that? what?

AV Trial #89

Time	Comment
0:00	hello, hello
	going to take me some time again to start talking about this stuff
	Jesus, here we go again, do you hear me? good
	well we do the whole thing again, oops, heat here
0:30	no no no, this one [turns on wrong valve]
	there we go, turn heaters, turn tubes and stuff
	this guy down, this guy down another way [adjusting valves]
1:00	this guys taking time, move it, move it
	ok now
1:30	not a very good time
	ok, now this heater must be used in a while
	oh oh turn this thing on a little bit [turn up heater 2]
2:00	everything seems fine, now we have to wait
	boring
	put him up a little bit [adjust heater 1]
2:30	oops turning this guy up a little bit, not too much, enough [adjust valve VB2]
3:00	he's sitting around the edge, no good, no good [referring to temperature 1]
3:30	reduce, reuse, recycle [picking up sheet of paper]
4:00	put this guy up a little bit, it's not nice, he's sitting too close to the ends [adjust heater 1]
4:30	this guy is too hot [adjust heater 2]
	better, I can't talk
5:00	this reducing water ...
6:00	ok it will change now any time, let's see
	there it goes

AV Trial #123

Time	Comment
0:00	here we go again, welcome to our show
	now we're turning on the valves, and we're turning on whatever
	very good
	now we're turning on the heater, ok, what?
0:30	ok, there we go again [turn on output valves]
	that will take a gizillion years to heat up, but ... oh gee [adjust valve setting]
	ok, let's see
1:00	oh good, it heated up
	very good, no let's fix here [adjust output valve 1]
	the output so we're losing water
	let's fix this guy here, so we'll try to accumulate some water there, accumulating [adjust output valve 2]
1:30	overheating, oh! [temperature 1 too high]
	ok
3:00	oops, overheating again [temperature 1 too high]
4:00	(singing)
6:00	it will change now
	gosh! [demand pairs change as he finishes speaking]

AV Trial #163

Time	Comment
0:00	no, I'm not ready, I'm not
	four, ok well [setting VB2]
	turn on the pumps again
0:30	ok let's see [examining heater settings]
1:00	oh boy! [temperature 2 too high, reduce heater 2 setting]
	almost lost this guy [reduce heater setting 1]
	(singing)
1:30	need some more water, too cooling down [adjust valve setting VB2]
2:00	absolutely too fast [adjust heater setting 1]
	sit shut [adjust heater setting 1]
2:30	this guys is losing here ... [examining reservoir 2]
3:30	reduce the water, it'll get heated up
	come on now
	good water [reduce valve setting VB2 slightly]
4:00	... oh good
	(singing)
4:30	(talk in Greek) [hears noise]
	Greek stuff to you, don't provoke me! [talking to experimenter]
	Greek stuff to you, Jesus Christ
5:00	all Americans bully, it seems that Americans are too bully for my taste man
	bullies, bullies, you know the neighbourhood bullies
	oh shit, now this is under the record too, I don't care, ok ok don't bug me now
6:00	solution? [demand pairs change]

AV Trial #165

Time	Comment
0:00	(singing)
1:00	ok, now we'll fix that
	that was fast, wasn't it? yes it was
1:30	huh?
	a little bit more, a little bit more water [adjust valve setting VB2]
2:00	good
3:30	oh boy, oh boy, oh boy, oh boy, oh boy, this is boring!
4:30	must!
5:00	reduce the rate of increase a little bit [referring to reservoir 2 volume]
	I wonder
5:30	okay! fifty-six [adjusts output valves to match new demands and checks time]

AV Trial #183

Time	Comment
0:00	all right, here we go
	turn heat
	heat and water
	oh boy
0:30	ok, one down, one to go [reservoir 2 reached steady state]
	ok
1:00	use the heat here, and use ... heat over there
1:30	down, down [adjust output valve 1 and heater setting 1]
	(singing)
2:00	this guy goes down [turn up valve setting VB2]
	we need more water over there [referring to reservoir 2]
3:00	put some water more, reduce this heat [adjust valve setting VB2]
	hey Chris, do you have a newspaper? [speaking to experimenter]
	no, from Quebec? [responding to experimenter]
4:00	oh boy, this guy gets a bit hot for my taste [referring to reservoir 1]
5:30	ok [demand pairs change]

AV Trial #187

Time	Comment
0:00	(singing)
	I don't forget to talk, I know how to talk!
	speak up my mind? ok, I'll speak of my mind!
	here we go ... again
0:30	put these things up, they are there [setting output valves and heaters]
	more heat, this is steady state right? [referring to reservoir 2]
	all right, 53 [referring to time]
1:30	oh good, that comes down [referring to reservoir 1 temperature]
	oh oh more, more heat [referring to reservoir 1 temperature]
	that looks better
2:00	(singing)
	reduce again just a little bit [output valve setting 2]
	get a little better, this bloody thing
	oh it's going to be an S.O.B., I hope ...
2:30	I think it's a little bit too much [output valve setting 1]
3:30	(singing)
5:30	ok any time now it'll change at about 53 or something [demand pairs change at 5:51]

AV Trial #209

Time	Comment
0:00	all right
	(singing)
1:30	all right these guys [adjust heater 1 setting]
3:30	damn [whispered, but no control actions]
4:30	Chris, when are you going to put all the results together? [talking to experimenter]
5:30	ok, put it down [adjust output valve settings to new demand pair]

IS Trial #63

Time	Comment
0:00	ok check the system's water levels [referring to demand pair]
	turn on the pumps
	pump ...
	heater one at 3/4, heater two half way -- be half full
0:30	ok
1:00	probably turn down that heat a little bit [adjust heater 2 setting]
	open the output valves
	and adjust input
	soon as these stable ... ok ... pretty good
	knock you down to 8 [adjust valve setting VA1]
	knock you down to about 6 [adjust valve setting VB2]
1:30	ok, can knock you down a bit more to 5 [VB2]
	going to put you up to full because reservoir 1 is taking a long time [adjust heater 1 setting]
2:00	so make a few adjustments [adjust heater 2 setting]
	one more
	one more, there
2:30	it's time to turn down the heat
	... not quite
	now it is [adjust heater 1 setting]
	so we watch for that line to go vertical, which is about there [referring to energy balance schematic]
3:00	and the system's stable
	need a bit more heat to reservoir 1
	the water levels are stable
	the temperature of reservoir 2 seems to be stable
3:30	reservoir 2, reservoir 1 rather, is just a little bit cold so I'm going to increase the temperature
4:00	ok turn it down [adjust heater 1 setting]
5:00	ok that ... feels that ... [mumbling]
5:30	so I'm pretty much ignoring the water level in each reservoir because they're stable, and just looking at temperature in the reservoirs
6:30	couldn't get much more stable than this
7:00	now I'm really just waiting for the conditions to change
7:30	there they go [demand pair changes at 7:40]
	ok this one's above 10 so I'm going to have to use VA2 ...

IS Trial #64

Time	Comment
0:00	here we go
	check the outputs, they're really high [referring to demand pair]
	two ... turn on valves
	turn on the pumps
	turn on the heaters
	and we wait
0:30	ok
1:00	so about now turn up, and up, turn on [turn on output valves and adjust input valve settings]
	and let's see what happens
	shall we ... [adjusting output valve settings]
	now I've got ...
	the outputs where I want them, going to have to turn down the heat [adjust heater 1 setting]
1:30	I'm going to need a bit more water ... going into there [referring to reservoir 2]
	a bit more heat going into there [referring to reservoir 2]
2:00	need still a bit more [adjusting input valve and heater settings]
	ok turn down that heat [adjust heater 2 setting]
	there ... it's about there
2:30	so ...
	I think I've pretty much got ... everything stabilized
	I'm just playing with the heat now
3:00	make sure ... just a little bit more [adjust heater 2 setting]
	just going to increase the output just a little bit on reservoir 1 because it's creeping up, the level that is
	uh, turn up the heat on reservoir 1 because it's minimal ... oops
3:30	reservoir 2 is just creeping up so turn that down a little [adjust heater 2 setting]
	so now I just keep an eye on things
4:00	ok it appears that pump 1 has failed

IS Trial #89

Time	Comment
0:00	so before I start I look at the output levels [referring to demand pair]
	I turn on the valves to ten [referring to input valve settings] before I turn on the water pumps
	for heater 1 I turn it on to full
	heater 2 I turn it on to half way
	I find those are the best settings initially to heat up the water
0:30	before I used to wait for the tank to be half full before I set outputs but lately I set them as soon as possible ... just to cut down the time really
	I'm going to need some extra output [adjust valve setting VO2]
	now I just wait
1:00	I want this to come down a little [adjust valve setting VA1]
	there we go
	turning down the heaters
	ok reduce input from the VB2 just to make this line vertical [referring to mass balance graphic for reservoir 2]
1:30	you know by doing that it usually lowers the total energy so I want to increase that [referring to heater 2 setting]
	lowered it a bit too much [referring to heater 2 setting]
	very annoying, that heater 1 is not getting up there
2:00	here we go
2:30	now reduce input just a touch [adjust valve setting VB2]
	reduce input just a touch [adjust valve setting VA1]
	again reduce input [adjust valve setting VB2]
	all I'm trying to do now is to stabilize the system
3:00	oh dear
	it's very difficult to do when your glasses are fogged
	there ...
	crazy room!
	so essentially I'm not concerned about the water input or output any more, I'm just concerned about maintaining the proper temperature
3:30	and...
	reservoir 2 seems pretty stable
	and so does reservoir 1, so I'm just keeping an eye on the temperature
4:00	ok reservoir 2 is slowly creeping up so I'm going to reduce the heater setting
	reservoir 1 is pretty stable
5:00	ok reservoir 2's temperature is dropping so I increase the setting
	reservoir 1 is now dropping so I increase it slightly [adjust heater 1 setting]
	reservoir 2 is going up [referring to temperature 2]
5:30	so really ...
	just trying to keep everything stable
7:00	ok the settings have changed [demand pairs change at 7:14]

IS Trial #122

Time	Comment
0:00	ok start the system, like to get an idea what outputs are [referring to demand pair]
	turn pumps on
	turn heat on to full
	there we go
	this heat down to about 1/4 [heater 2 setting]
0:30	so ...
	let's see, everything's going well so far
	now I set outputs -- that's about 3 so I set input to about 3 [adjust valve settings VO2 and VB2]
	again this output is 2, 4, about 5 [referring to reservoir 1]
	I'll let it go because of that heat, it's still pretty low
1:00	turn down the heat for heater 2 because it's about to go over
	it's time to open the output valve for reservoir 1 [adjust valve setting VO1]
1:30	and set this to input [adjust valve setting VA1]
	before it overflows [reservoir 1]
	now unfortunately the temperature of reservoir 1 is not high enough yet, it's going to take a while
	I'm going to just dump a bit of the water out [adjust valve setting VO1]
2:00	ok I'm going to turn the heat off completely in reservoir 2
	ok there we go
	turn the heater back on for reservoir 2
2:30	while all the while keeping an eye on reservoir 1
	there we go [adjusting heater 1 setting]
	I think that's pretty much stable
3:00	I'm going to reduce input to reservoir 1 [adjust valve setting VA1]
	increase the heater setting [adjusting heater 1 setting]
	ok I'm going to reduce it a little bit more [adjust valve setting VA1]
	see before I used to wait for the reservoir level to get about half full before I really bothered setting the heater or output levels, but now I do it as soon as I can, it just seems easier that way
3:30	ok heater 1 is sitting a bit high so I'm going to turn it down
	and things look fairly stable
4:00	heater 1's increasing a little bit too fast ... the temperature in reservoir 1 so I'm going to ... do that
	the temperature in reservoir 2 is dropping so I'll increase the heater setting
	excuse me
4:30	pretty much ignore water levels unless something drastic starts to happen
5:00	well, nothing's happened
5:30	not waiting for the reservoir to fill up before stabilizing has gotten me into trouble a couple of times but I still feel like it's worth doing because it

shaves a few seconds off the time
6:00 not that that's a legitimate reason
6:30 well it should be comes up to 5 minutes in about 30 seconds [6:57-7:02]
7:00 ok that's relatively good news, I don't really have to look at too much changing going on [demand pairs change at 7:20]

<u>IS Trial #163</u>

Time	Comment
0:00	ok start up, check outputs [referring to demand pair]
	I always set input to both reservoir 1 and 2 at maximum
	I set heater 1 to maximum and heater 2 to about half from the beginning
	I like to wait for a little bit of water
	... to get into reservoir 2 before I do anything, turn down the heater 2 to 1/4
0:30	output to 3 reservoir 2, input to 3 [adjust valve settings VO2 and VB2 to 3]
	just keeping an eye on reservoir 1
	ok
1:00	that's good, set output to 4 reservoir 1, input to 4 [adjust valve settings VO1 and VA1 to 3]
	yah I can ignore reservoir 2 for the next little while
	not too much though, turn up the heat [adjust heater 2 setting]
1:30	and now it's time to turn down the heat in reservoir 1
	ok
	ok I got some good numbers here
2:00	at least partially balanced
	before 2 minutes, so around 7 minutes I should start looking around
	ok ... since the level is so low in reservoir 2 I'm just going to have it slowly increase
	reservoir 1 I'm just going to try and maintain at that level, although it's not important
2:30	so I want the temperature to rise a little bit in reservoir 1, and it's fallen enough in reservoir 2 so I'll increase the heat
3:00	ok I'm going to turn down ... grrr ... turn up the heat in reservoir 2, turn it down in reservoir 1
	let's see how that works
3:30	really nothing interesting's happened yet
4:00	just keeping an eye on the temperature as I'm not concerned about water level
	usually if something's wrong with water level I notice because the heat changes
4:30	pretty confident that reservoir 2 is stable, so I'm paying more attention to reservoir 1
5:00	turn down reservoir 1, turn down the heat
6:00	occasionally the mouse is sticking but it's not much of a problem
6:30	ok settings have changed [demand pairs change at 6:37]
	pretty easy to accommodate

IS Trial #165

Time	Comment
0:00	so it's started with the outputs [referring to demand pair]
	intake to maximum [adjusting input valve settings]
	heater 1 to maximum, heater 2 to half
	and I wait a little bit
	just making sure those are on maximum [adjusting input valve settings]
	ok turn heater 2 down slightly
0:30	time to set output for reservoir 2 to 7 [adjust valve setting VO2]
	input to 7 [adjust valve setting VB2]
	still plenty of time to worry about reservoir 1
	nothing unusual's happened yet
1:00	there we go, turn down the heat a little bit [adjust heater 2 setting]
	output to 8, input to 8 [adjusting valve settings VO1 and VA1]
1:30	turn down the heat for reservoir 2 slightly
	and time to turn down the heat for reservoir 1
	there we go
	turned down too much, got to heat it up a little bit [adjust heater 1 setting]
2:00	unfortunate when you're right at the interface it's very difficult to see
2:30	ok
3:00	everything should be fine now
3:30	and so now we wait
	as long as the temperature of each reservoir is stable I'm not concerned about anything else really
4:00	reservoir 2 is creeping up [adjust heater 2 setting]
4:30	ok reservoir 1 is creeping up a little [adjust heater 1 setting]
7:00	ok the settings have changed [demand pairs change at 7:15]

IS Trial #183

Time	Comment
0:00	start off, both outputs are reasonable so don't worry about it [referring to demand pair]
	pump and input to maximum
	heater 1 to maximum
	inputs to maximum for reservoir 2
	and heater to half [adjusting heater 2 setting]
	so ... output is 3 for reservoir 2 so I'll set that to 3 [adjust valve setting VO2], turn down the heater [adjust heater 2 setting]
0:30	set input to 3 [adjust valve setting VB2]
	and I won't ... just make sure the heater setting is good for reservoir 2
	set output and input for reservoir 1 to 6 [adjust valve settings VO1 and VA1]
	ok the heater's too high for reservoir 2 so I've turned it down
	turned it down some more
1:00	going over but that will be ok
	so now I turn down heater 1
	and perfect
	set heater 1
	just waiting for reservoir 2 to cool down a bit before I adjust it a bit more
1:30	perfect, turn it up and increase the input [adjust heater 2 setting and valve setting VB2]
	reservoir 1 ...
	and increase heater 1
2:00	so that should be fine
	well it's just a matter of waiting now to make sure everything's stable
2:30	turn up reservoir 2, or the temperature of reservoir 2
	that should be stable
3:00	I'm keeping an eye on the temperature of reservoir 1
	just want to increase it a little bit [adjust heater 1 setting]
4:00	ok I'm going to turn down the heat in reservoir 1 and see if I can stabilize it
	I figure the settings are going to change at around 6:45 so I have 2 and a half minutes to wait
4:30	so it's stable so I don't need to do anything
6:00	so things have changed a bit earlier than I expected, but I can live with it [demand pairs change at 6:21]

IS Trial #187

Time	Comment
0:00	ok trial 187, outputs are good [referring to demand pair]
	input valves to maximum on both reservoirs 1 and 2
	heater 1 to maximum, heater 2 about 3/4
	and so far everything's behaving normally
	I'm going to set output for reservoir 2 at 7 [adjust valve setting VO2], and I'm going to set input at 7 [adjust valve setting VB2]
0:30	turn down the heater to about half [adjust heater 2 setting]
	ok that's pretty good
	turn up the input a little bit [adjust valve setting VB2]
1:00	ok everything's fine for ...
	reservoir 1 set output to 6 [adjust valve setting VO1], set input to 6 [adjust valve setting VA1]
	ok that's good
	and just waiting to ...
1:30	turn down the heater now [adjust heater 1 setting]
	and that's about it
	heater a little bit [adjust heater 1 setting]
	turn up a little bit more
	that's pretty good
	turn up heater on reservoir 2
2:00	so I'm just making a few adjustments, everything's stable
	so I wait until about 6:45 for the settings to change
	unless, of course ...
2:30	oh dear ... I might not have read the heater, the temperature setting on reservoir 1 properly so it might be a bit longer
	yah I don't think I did, ok well, it'll be 7:30 then ... when the settings change
3:30	and everything's fine
4:00	excuse me [clears throat]
	turning down heater 1 because the temperature on reservoir 1 is creeping up a little
4:30	turn it down a little bit more
6:30	yup how annoying
	I thought for sure I read that temperature properly but I obviously didn't
7:00	there we go [demand pairs change at 7:38]

IS Trial #209

Time	Comment
0:00	outputs are good so valves and pump on [referring to demand pair]
	maximum as usual [adjust input valve settings]
	heater 1 to maximum, heater 2 to half
	ok set output reservoir 2 at 6, input to 6 [adjust valve settings VO2 and VB2]
1:00	ok top up 1 a little bit
	set output to 5, input to 5 reservoir 1 [adjust valve settings VO1 and VA1]
	and time to turn down the heater [adjust heater 1 setting]
1:30	ok looks like 1:40 was in the limits
2:00	let's see ... increase input to reservoir 2 again [adjust valve setting VB2]
	and I wait
3:00	and time to turn down the heat on reservoir 1
6:00	the settings should change in about 30 seconds [6:16-6:19]
6:30	and it's good [demand pairs change at 6:36]

IS Trial #217

Time	Comment
0:00	away we go
	output for reservoir 2 is low [referring to demand]
	valves and pump on to maximum
	heater 1 to maximum, heater 2 to about a half
	and I wait a little while
	ok turn down heater 2 to 1/4
	reservoir 2's output to 2, input to 2 [adjust valve settings VO2 and VB2]
0:30	ok turn down the heat ... to reservoir 2
1:00	perfect
	set output reservoir 1 to 5, input to 5 [adjust valve settings VO1 and VA1]
	and watch the heat
1:30	ok I think it's about time to turn down the heat for reservoir 1
	there
2:00	just touching up the heat for reservoir 2
	reservoir 1
	and that should be good
2:30	so far so good, all readings match the settings
	and we just wait
3:30	turning down heater 1 just slightly
4:00	and turning down heater 2 slightly
5:00	better turn down heater 2 ... or heater 1 slightly
5:30	reservoir 2 seems stable
	and reservoir 1 seems fine
	and I turned down the heat a little too much [adjust heater 1 setting]
6:30	and settings have changed [demand pairs change at 6:35]
	not too drastically, so that's good

<u>ML Trial #64</u>

Time	Comment
0:00	ok
	yup, it seems to be [in response to experimenter's question]
	same deal, I'm not going to explain it all again
	adjust the heat high here, because we're going to be pumping lots of water out [adjust heater 2 setting]
	and this is 2,3; this is 2, 4, 6, 8, 10, 12, 14, 16, so it's 19 [referring demand pair and their total]
0:30	so all of the water should be going into this one [referring to reservoir 2; turn off VB1 and adjust VB2 to maximum]
	oh ... I forget this thing is set loosely
1:00	so this is around 16, this is, what?, almost 30 [reservoir 1 and 2 volumes]
	temperature's ok here [reservoir 2 temperature]
	here we're still getting up there [reservoir 1 temperature]
1:30	probably it should be around 4 or so [heater 1 setting]
	this is still going bananas?, it's funny [reservoir 2 volume]
	pull back? no pull this back [adjust valve setting VB]
	this is sitting around 18, 33 [reservoir 1 and 2 volumes respectively]
2:00	hey we're in there!
	now are we going to overshoot? [reservoir 1 temperature]
	yes
	we're close to 2 minutes
	once the temperature starts dropping, I'll put some more water in there
2:30	learning smart heats ... I know what I mean!
	let's try on 3 or was it 4? [adjust heater 1 setting]
	it'll probably be around 4
	this can come down [adjust heater 2 setting]
3:00	4, are we holding or are we rising? [reservoir 1 temperature]
	rising! won't touch it yet
	it's 20, 30 ... 3, 4 that's about where it was before, I think this is fairly stable now [reservoir 2 volume]
	oop heat's getting a bit high, turn it down to 3.5 [reservoir 1 temperature]
3:30	ok bring it down to 3 [adjust heater 1 setting]
	now, if it drops at 3 we know it's between 3 and 4
	that's at least something
	this is still rising a little, this is rising a bit [reservoir 2 and 1 volumes]
4:00	so let's bring this down ... to a little over 9 [adjust valve setting VA]
	this is still rising! [reservoir 1 temperature]

ML Trial #89

Time	Comment
0:30	[tape starts at 0:42]
	the temperature, temperature is fucked!
	and it's not quite there yet
	this one is 7, it seems to be right around 7 [reservoir 1 demand and heater setting]
	this one I just don't get! [heater 2 setting]
	let's try right there
1:00	take a look at the water, see how the water's going
	check our levels and make sure they're where they're supposed to be
	on these inputs, water inputs, this temperature's almost up to where it should be, and I'll just put it up to 7.5 [heater 1 setting]
	this one is slowly coming down, let's put it down to 4 now, and let it work back up [heater 2 setting]
	water's still rising here, why? [reservoir 2 volume]
	11, 11 and 7, maybe I've screwed the numbers now [demand pair]
1:30	I've put 10 and 6, it's not quite the same so let me put 6.5 for both of them and see if that straightens out the water levels [adjust valve settings VA1 and VB1]
	that's in the range now, that seems ... let me pull it down just a touch [adjust heater 1 setting]
	this one's still not down enough, I'll put it down to 3 and a bit, 3.75 or so [adjust heater 2 setting]
	there that's in the range now and it's 2 minutes -- happy day!
2:00	watch the water levels, what are we at? 27 and 25ish [reservoir volumes]
	27 and 25ish ... that should go up so we'll pull that down, back down to 7, a little under 7, just barely [adjust heater 1 setting]
	this is now dropping again, that's good
2:30	now it goes ... still about 27 and 25ish, that's encouraging [reservoir volumes]
	this is looking moderately stable this temperature [reservoir 1 temperature], this is coming back down, just watching to make sure it doesn't come back down too much [reservoir 2 temperature]
	this is down too much -- put that up again, just a click [adjust heater 2 setting]
	water level's still rising in this one, so the way I think I'll deal with that is just to put the output up a little bit, so it's still within the range but a just bit more water is coming out [adjust valve setting VO2]
3:00	this is still holding around 25ish, I think that looks pretty good [reservoir 1 volume]
	temperature is stable-ish [reservoir 1 temperature]
	this temperature is still a little low, crank it up a little bit more see how that

	goes [adjust heater 2 setting]
3:30	all right they all seem fairly stable, although this temperature hasn't moved up even though I've put the heater up a bit whoops, I saw it drop a titch [reservoir 2 volume] that's ok -- I can always pull back the output it seems fairly smooth, looks like it might be up a little bit ... this temperature is still not up so I'll click it one more time so I can get a little bit more out of it [adjust heater 2 setting]; and this one's dropped a bit
4:00	I'll click that as well just to get a smidgen more out of it [adjust heater 1 setting] no, I won't, I'll click it back down and what I will do is cut off a little bit of the water going to that, open that one back down to 6 [adjust valve setting VA1]
4:30	the reason I'll do that is because I notice this is going up slightly [reservoir 1 volume] and this is going down slightly [reservoir 2 volume] that will balance off the water, less water going in and the temperature won't need to be clicked higher this is ok-ish, so we're at fairly stable just now coming up to 5 minutes, that's 3 minutes of being in the ranges, still got 2 minutes to go ... before the change
5:00	everything seems sort of ok, this is holding around 27 and 25 which means we're quite stable right now [reservoir volumes] time to get my coffee ... [leaves]
6:00	I'm back a minute later, the temperatures haven't moved water levels are still around 27-28 and 25 there's been absolutely no change except I have coffee now hot coffee, fresh hot coffee whoops, there goes the change [demand pairs change at 6:27]

ML Trial #122

Time	Comment
0:00	122 ... this is trial 122, yah!
	2, 4, 5 and 3 is 8, [referring to demand pair (5,3)] half and half is 4, 4 ...ah I said 4, 4 [adjust valve settings VA and VB]
	oh hang on here, oh hang on here!
0:30	3, 3, 4, no, no, 5, 5, 5, 3, 5, 3, [adjust valve settings VA1 and VA2] 5, 3, [adjust valve settings VB1 and VB2] open, open [open output valves]
	and it is ...
1:00	just fine tuning 3, 5, 3, 5, 3, 4 and 4 looks all ok
1:30	(humming)
	2, all right just before 2 minutes at this point
2:30	so we just ... open them up
	4 and 4 is eight, 3 and 5 or 5 and 3 is eight, 5, 3, 5, 3, [checking valve settings] 5, 1/3 of 3 is 1, [checking heater settings] can I tell you?
3:00	but so far so good
	looks like wait ... that was around just before 2 minutes that I eased this one into range, everything else was there, just this one [reservoir 2]
	so around 7 minutes they should change again, maybe a little bit before
4:00	just tell that ...
6:30	[demand pairs change at 6:51]

ML Trial #165

Time	Comment
0:00	start up, opening everything about half way to get the water flowing [open all input valves]
	go over, we want 8 here and about 3 here [adjust heater settings]
	so I'll put on that... 8 plus 7 is 15, half of each, 7.5, 7.5, [adjust valve settings VA and VB] 8, 7, [adjust valve settings VA1 and VA2] 8, 7 [adjust valve settings VB1 and VB2]
0:30	output [open output valves]... eight [adjust heater 1 setting]
	let's go, let's go, get in there, there we go
	that one is just over 2
	check this out ... 8, 7, 7, 8 ... [checking settings]
1:00	looks ok
	getting a little hot [adjust heater 2 setting]
	somewhere around 40's [anticipating time at which demand pair will change]
1:30	so I'm going back to my reading and checking up every once in a while
3:00	looks ok so far
4:30	so far so good
5:00	oops, watch for the change
5:30	[demand pair changes at 5:48]

ML Trial #183

Time	Comment
0:00	start up as normal, open the valves, ah! [open input valves VB, VB1, VB2]
	turn the pump on and open the valves [open input valves VA2, VA1, VA]
	turn the pump on, letting the water to flow in
	set the temperature so it starts warming
	3 and 6 is 9, so 4.5, 4.5, [adjust valve settings VA and VB] 6, 3, [adjust valve settings VA1 and VA2] 6, 3 [adjust valve settings VB1 and VB2]
0:30	open these
	and fiddle with the temperature
	I should adjust this better [adjust valve settings more accurately]
1:00	6, 3, 6, 3
	should stabilize around there
1:30	whoops this temperature's too high, pull it down [adjust heater settings]
	and set it back up
2:00	fiddle with these
3:00	that's ...
6:00	going to adjust the stability since it looks like it's losing a bit of water [adjust valve setting VO2]
6:30	ok that's the new settings [demand pairs change at 6:42]

ML Trial #187

Time	Comment
0:00	open the valves, turn the pump on [open valves VB1, VB2, VB] open the valves, turn the pump on [open valves VA2, VA1, VA] put some heat on [turn on heater 1] put some heat on [turn on heater 2] 7 and 6 is 13, [demand pair] 6.5, 6.5, [adjust valve settings VA and VB] 6, 7, [adjust valve settings VA1 and VA2] 6, 7 [adjust valve settings VB1 and VB2]
0:30	6, 7, and 6, 7 [checking valve settings]
1:00	Lorellen has found a lap ... [speaking to experimenter]
6:00	[demand pairs change at 6:09]

ML Trial #209

Time	Comment
0:00	open the valves, start the pumps, same as always
	then what were you doing in Vermont then? what were you doing in Vermont then? [talking to experimenter]
	I thought you were looking through Lake Placid and that [talking to experimenter]
	ok, so you didn't go as far as Maine [talking to experimenter]
	wow! [talking to experimenter]
1:00	2, 4, 5, 6 ...
	for what? [talking to experimenter]
1:30	here! [talking to experimenter]
	what crisis? [talking to experimenter]
2:00	hmmm ... very sensational! [talking to experimenter]
	it's a crisis! [talking to experimenter]
	what are you doing -- what am I doing? it should be 5 [adjust heater 1 setting]
3:30	ah!
6:30	it's in the car [talking to experimenter]
	yah, you're just going out for a few minutes [talking to experimenter]
	well then just grab mine, off ... oh they're upstairs on the ... [talking to experimenter]
7:00	yah it's upstairs on the corner [talking to experimenter]
	yah this is the last one [talking to experimenter]
	this is the last one [talking to experimenter]
	no, this is the last one I'm recording [talking to experimenter]
	pardon, I hope so [talking to experimenter]
	what the hell's going on here?
	all right something's going wrong there

TL Trial #63

Time	**Comment**
0:00	uh ... and here we go again
	the real question today is does he remember what he's doing after so many days off?
	so starting off as usual and turning the valves and the pump on to the associated reservoirs
	and oops we're made this mistake before haven't we? [adjust heater 2 to full and then change to half]
	and we're just cranking up the heat
0:30	adjusting the input and output valves so that they agree
1:00	turning down the heat a bit
	doing likewise on reservoir 1
	excuse me
1:30	stop the pump for a while, hopefully we'll build up the heat faster [turn off pump PA]
	here we go, we're getting there
	now we turn the pump back on, yah
	turn the heat down [adjust heater 1 setting]
2:00	better crank up the heat a bit [adjust heater 2 setting]
	and again that's just a rule of thumb
	the steady state heater setting for reservoir 2 is about 1/3 the output and for reservoir 1 is about the same as the output
	we're starting to lose it a bit here [adjust heater 1 setting]
	just bear with me
	aw nuts
2:30	as you see I over reacted to adjusting the temperature in reservoir 1 so just need to wait for it to build up again but we've lost some valuable time
	so I guess the old pro is a little rusty after his lay off
3:00	(whistling)
4:30	(singing)
5:00	just making fine adjustments trying to keep the temperature in the desired range
6:00	not doing much here, just fooling around
7:30	oops ... falling asleep there [demand pairs change at 7:48]

<u>TL Trial #64</u>

Time	Comment
0:00	and we're off again, trying to redeem ourselves this time
	standard start-up procedures [turning on pumps and input valves VA, VA1, VB, VB2]
	holy cow! as we see very high demand here in reservoir 2
	so we'll need to make a few adjustments here [turn on VA2]
	there, so now the input is about the same as the output
	oh yah temperature whoopsie [adjust heater settings]
1:00	since there's lots of water coming in we're going to need to pump up the temperature on that reservoir [adjust heater 2 setting]
1:30	oops oops oops oops overshot it there [adjust heater 1 setting]
2:00	things are getting too hot everywhere [adjust heater 2 setting]
	ok now the inflow to each reservoir the same as the output, input is the same as the output
	and now just looking to find that great steady state temperature
2:30	again rule of thumb: heater setting at the same as the output setting on reservoir 1 and 1/3 the output setting on reservoir 2
4:30	what the heck!

TL Trial #89

Time	**Comment**
0:00	here we go welcome back DURESS fans from the holidays and what we're trying to do is get the system going just as soon as we possibly can so for reservoir number 2 we're opened the valves wide open and put the heat at setting number 4 again as you recall from last time the setting for heat, or steady state setting for heat, on reservoir number 2 is around 1/3 of the input water level
0:30	so here we're getting close and there we go we're just going to set the output going and looks like we've missed a bit, unfortunately, on reservoir number 1 and what we're trying to do now is just fill the reservoir up to about 60, and I'll explain why a little later
1:00	for reservoir number 1 I set it originally 7 and the heat at 10 just to try to get that temperature up there as soon as I can in order to start but now things are pretty cold so I'm going to shut things down and just see if we can't keep that water up a bit [turn down VA1 and VO1]
1:30	just making a little fine adjustment on reservoir number 2 my apologies for not being very coherent, just trying to concentrate on the task at hand here so let's try that again [turn up VO1 and VA1] and I'll set it to 8 just so that things will fill up a bit [adjust VA1]
2:00	and increase that a bit so that will continue to fill [adjust VA2] so we take note that we reached steady state at approximately 2 minutes so we can keep an eye on things that way we can anticipate when we'll need to change the levels
2:30	things are always a little trickier on reservoir 1 to bring to a steady state just because we need it to be a higher temperature and usually we're working with a little less water just through the ways I'm doing things
3:00	just making little adjustments to the heater to try to keep the temperature well within the desired area
4:30	so as we see in reservoirs 1 and 2 we're getting pretty close to the 60 mark which is pretty well where we want to be for the steady state
5:00	and again, just to keep you on your toes, I'll explain why later so you see what we try to do here is to try to get things going as quickly as possible and then fill the reservoir while the system is in steady state
5:30	the alternative is to fill it to the 60 and then reach the steady state which is probably a little easier in terms of manipulation but would cost us a lot in time and likewise ...
6:30	oh things getting a little toasty in reservoir 1 so let's bring down the heat oh change is desired, so we quickly react to these changes and try to bring things to a steady state [demand pairs change at 6:54]

TL Trial #122

Time	Comment
0:00	here we go we're back again to recording DURESS trials so now we're just starting up the system what we're trying to do is get things going as quickly as we possibly can so in pump B we're trying to use that to fill pump ... reservoir 2 rather and then with pump A we're trying to fill reservoir 1
0:30	see now in pump A we're only letting things go at about 7, that's just so that things heat up a bit quicker, and then we increase the water level to 10 once it looks like it's going to hit the steady state [adjust valve setting VA1] in pump B what we did was to start off with a heat level of 4, heat things up, and then turn it down to 3 when it looks like we're going to get close to steady state [adjust heater 2 setting]
1:00	so now things are progressing rather nicely and we're just going to let things fill up to a level about 60 or 70 or so in the reservoir just to be able to take into account contingencies if they should occur because the system doesn't always work like you figure it would [referring to reservoir volumes]
1:30	so now reservoir 2 looks like it's about ready so we start turning things down so that the input level equals the output level and the level is maintained within reservoir 2 [adjust valve setting VB2] we put the heater level down to 1 which if you've seen the previous DURESS shows is my rule of thumb where to set heater levels for the steady state which is for reservoir 2 about 1/3 the input water level and for reservoir 1 it should be about the same
2:00	probably something not too scientific about that just something that has happened to work out so now we're ready to ... bring the level in reservoir 1 to a steady level whereby the input now equals the output [adjust valve setting VA1]
2:30	and we've made a little mental note that the original steady state conditions were reached, that is the output levels and output temperatures were reached at approximately 45 seconds, so at approximately 5:45 we can expect to need to react to a change in demand just making a slight adjustment here in order to make sure the input and the output are the same [adjust valve setting VO2]
3:00	things are heating up just a hair in reservoir 1 so we'll turn down the heat a little
3:30	similarly things are heating up just a trifle too much in reservoir 2 so we'll turn that heat down about half a step also now that things look like they're at the level we want we'll just turn heat up a hair and try to maintain it there, likewise with reservoir 1

5:00 when the demands in output does change we're going to change the two outputs from two reservoirs to reflect that immediately as to have us meet those conditions as soon as we can, and then we'll adjust the heat and the input level to match that

5:30 just adjusting the heat there a bit because things are getting a little too cool [adjust heater 2 setting]
oops here we go [demand pairs change at 5:44]

TL Trial #163

Time	**Comment**
0:00	here we go
	valves wide open for reservoir 2 [open input valves VB, VB2]
	heat setting at 4 [adjust heater 2 setting]
	valves at setting number 7 for reservoir number 1, heat setting till 10 [open input valves VA, VA1]
	that's just so that things heat up a little faster in reservoir 1 since they need to get just a little hotter
	so now we're approaching desired temperature range
	we get the valves going [open output valve VO2]
	turn down the heat, get the output valves going [adjust heater 2 setting, open output valve VO1]
0:30	and turn up the water [adjust valve setting VA1]
	so now we're going full blast in both reservoirs
	the temperature should stay within desired range, the outputs are in the desired range, and we are just waiting for both reservoirs to fill up to around level 60 or so
	that's so that we have enough water in the reservoirs to adjust ourselves to any change in demand, any problems like broken valves or something, and ultimately at the end just have enough water in the reservoirs to drain and cool down so we could shut the input valves off a little earlier before the desired shut-down time
1:00	(whistling)
1:30	and so we see reservoir 2 getting past 60 so we're going turn the input valve and likewise we turn down the heater [adjust valve setting VB2 and adjust heater 2 setting]
	for reservoir 2 we turn the heater down to about 1/3 what the input water level is
2:00	and now for reservoir 1 we do sort of the same thing, turn the heater down and turn the water down
	and here we're just going to put it a hair under 2 which is the same as the input level [adjust valve setting VA1]
	and just adjusting it
	try to keep that temperature range where we want it
2:30	so now you've got about 70, level 70 in each of the reservoirs, which is all right, 60's good just to ... but 70 sometimes you've just got too much and you need to drain out
	just need to pump up the valve a bit ... on reservoir 2 [adjust valve setting VA1]
3:00	still going down, but let's ... let's pump B in there ... [open valve VB1]
	yah that's good
	reservoir 2 going down

3:30	oh nuts ... let's get some heat [adjust heater 1 setting]
	I should have kept an eye on that, I was distracted unfortunately
	come on guys, heat up
4:00	might as well shut PA off, it's not doing us any good
	so that's ...
4:30	something's funny, looks like PB ain't working so high [adjust VB1, turn on pump PA]
	oops, better turn the heat down now [adjust heater 1 setting]
	aw nuts!
5:00	having a hard time here
	looks like PA is pumping in something, just not what we expected it to be
6:30	hard to tell if that's in the range or not
	well that's definitely in the range
7:00	well doing pretty good until I turned PA off, I think
	but heck that's life
7:30	oh here we go again!
8:00	hello! oh there we go
8:30	hmm ... PA looks pretty good, many I goofed up totally, lost my mind there for a brief moment
	let's try something
9:00	well I might have lost my mind as it's documented on tape now
	maybe I misread the output demand -- roll back that tape
	which would explain a great deal of things
	it appears that I have lost my mind
9:30	nothing wrong with the valve, just me misread the output demand
10:30	oh how embarrassing!
11:00	what the heck's happening here?
11:30	get some more water in there, draining a bit too much [adjust valve setting VB2]
	some heat in there, falling a bit too low [adjust heater 1 setting]
12:30	oops, but what the ... [demand pairs change at 12:55]

TL Trial #165

Time	Comment
0:00	and away we go [adjust input valve settings VB, VB2]
	same start up as always
	we have level 7 going into reservoir 1, with heat setting at 10 [adjust input valve settings VA, VA1]
	and full blast into reservoir 2, setting ... heat setting at about 4 [adjust heater 2 setting]
0:30	and we jack up the water to full blast in reservoir 1 [adjust valve setting VA1]
	compensate for the high heat setting
	and likewise we turn the heat down a bit in reservoir 2
	and just wait till things fill up now
2:00	(wipe screen)
	getting up to the 60 level in reservoir 2
	there we go [adjust valve setting VB2 to output]
2:30	now we'll just keep an eye on temperature
	make sure it stays within the same level
	there, I think we need to turn it down a bit
3:00	so there you have it, heater setting approximately 2/3 that of input water level
4:00	alrighty, so in reservoir 1 we're getting close to that magic 60 level mark
	so turn down the heat, turn down the water [adjust heater 1 setting, adjust valve setting VA1]
	the heat level, same as the water level, numerically anyways ... and for reservoir 1
4:30	it's getting a little toasty there [adjust heater 1 setting]
5:00	so we're looking for a change in demand to come around 5:45 or so
5:30	that's interesting ... [looking at screen through magnifying glass]
	[demand pairs change at 5:42]

<u>TL Trial #183</u>

Time	Comment
0:00	and we're off [adjust valve settings VB, VB2]
	letting the water pour right in into reservoir number 2 [adjust heater 2 setting]
	initial water level setting of 7 for reservoir number 1, heater setting at 4 [adjust valve settings VA, VA1, heater 2 setting]
	... for reservoir 2, likewise 10 for heater setting reservoir 1
	just to help heat things up just a little quicker [adjust output valves VO2, VO1]
0:30	setting output levels, turning down the heat a bit so they're more manageable, turning up the water to compensate for the rising heat level in reservoir 1 [adjust valve setting VA1]
	so entering steady state at approximately just under 40 seconds
1:00	once the water levels reach 60 we're going to try to maintain it at that level and then wait for the change ... change of demand to come
	and we're nearing that level so let's turn down the heat and the water level [adjust heater 2 setting, valve setting VB2]
1:30	reservoir 2, the heater setting rule of thumb, approximately 1/3 of the input water level
	heater 1 about the same as the input water level
2:00	let's turn down the heat a hair [adjust heater 2 setting]
	try to keep the temperature in that desired range
	and reservoir 1 is closing in on the 60 mark, so getting ready to bring down the heat and water level in there too [adjust heater 1 setting, valve setting VA1]
5:00	just making small adjustments to keep the temperature in the desired range
5:30	getting ready for a change in demand [demand pairs change at 5:38]

TL Trial #187

Time	Comment
0:00	[trial videotaped but subject made no verbal comments]

TL Trial #209

Time	Comment
0:00	here we go, it's still Monday morning the previous trial was rather embarrassing for all concerned -- well just me I guess [no further comments during start-up]

WL Trial #63

Time	Comment
0:00	now I start on first reservoir some more output and then the maximum input of the ... [set all input valves to maximum, heaters about half] so I can quickly rise up to the required level
0:30	now look at ours here, let's vary the output it's 8 for the first reservoir and 6 for the second [referring to demand pairs]
1:00	see the level of water is up now the temperature is also more close to the required reservoir almost close to half water capacity we set the appropriate input, let's say for first it's 8, we set 4 and 4 there [set input valves VA1 and VB1 to 4], second 3 and 3 there [set input valves VA2 and VB2 to 3]
1:30	and then get output correctly [adjust output valves VO1 and VO2 to demand]
2:00	well that's just to make sure that the input is correct now we see the water level stays stays there and temperature goes on rising well stable water level meets the input and output have reached equilibrium
3:00	now right not we doing some change to choose the best heating level to get the temperature stable there [adjust heater settings]
5:30	well the change means the choice just a moment ago is not correct or not the best [referring to heat settings] it takes a few tries to find the correct one actually
6:00	now it's better than previous case oh come away
6:30	we're going to watch for these for a while see while the temperature still keeps on going up or comes down now we can set the heating level accordingly
7:00	yes it's better it almost stays there still
7:30	well you see the reason for the first heating level is higher than the second one is due to the fact the requirement of the first one, 40°C, almost twice the second one
8:00	now there is a new requirement which is comes to 3 and 3 [demand pair changes at 7:59]

WL Trial #64

Time	Comment
0:00	when they start to turn on [open input valves] ... just trying to see ... to the first reservoir [turn on heaters] look at quick temperature increase and also, also fast water accumulation in the reservoir
0:30	and now we can take a look at what's the required output first one is 3 and second one is 14, what 16 there [referring to demand pair] when the water reaches the half mark of the reservoir capacity we can turn on, like I said, the appropriate input water flow because in that way the response will be more stable
1:00	the first one's 3 so we set 2, 1 [adjust input valve settings VA1 and VB1] this one is 16 so we set 8, 8 [adjust input valve settings VA2 and VB2]
1:30	we see increase the water when decrease the temperature in the reservoir
3:00	we see this response for first try so it's too low but ... [adjust heater setting] 3 may be appropriate, this one maybe 5 [referring to heater setting]
13:30	takes a long time in this case

WL Trial #89

Time	Comment
0:00	firstly I turn on the input on to maximum [open all input valves to maximum]
	and turn on two pumps to allow first accumulation of waters
	and also you should turn on the heater to quickly let the temperature reach what's required
	now we can take a look at what's desired output of volume
0:30	first one is 7, and then second one is about 11 [referring to demand pairs]
	we can divide them equally in two sections
	now we can lower this heater a little bit [adjust heater 2 setting]
	want not to overheat it
	this 7 can be 3.5 and 3.5 [adjust input valve settings VA1 and VB1]
1:00	this 11 could be 5.5 and 5.5 [adjust input valve settings VA2 and VB2]
2:00	the remaining thing is mainly to stable the temperature
2:30	choose an appropriate temperature level
	we are giving first a trial, I see what response to this temperature will be
3:00	this seems fine, it's quite close to the correct range
	oops, a little bit lower to make sure that ... overheated ... not [adjust heater 2 setting]
	in this case seems that 4.5 might be appropriate [referring to heater 2 setting]
3:30	now we think the system is quite stable
4:30	now the system almost reach equilibrium
5:00	now we can just wait for about 5 minutes
6:30	now we can quickly switch it to the other requirement [demand pairs change at 6:52]

WL Trial #122

Time	Comment
0:00	now first we turn on the input valves and the valves [open all input valves to maximum]
	and quickly set the heater level
	so the water will be accumulating in the reservoir
	and we take a look at what's the required output
	first one it's 5, and the second one is 3 [referring to demand pair]
	therefore basically I will be dividing the requirements into halves
0:30	for example the first one will be 2.5, second one will be 2.5 too, and it comes to 5 totally
	as long as water reaches appropriate level, we can set the required output 2.5, 2.5 [adjust input valve settings VA1 and VB1] and that's 3, so ok 1.5, 1.5 [adjust input valve settings VA2 and VB2]
1:00	there we can ... the tuning
1:30	so both the output and the temperature are reaching the required range
	of course, a separate change is necessary to find the correct choice of both heater settings
6:00	now we have to switch to the new requirements [demand pairs change at 6:14]

WL Trial #163

Time	Comment
0:00	now first we quickly turn on the input system [open all input valves to maximum]
0:30	two ... [referring to half reservoir 1 demand, adjusting input valves VA1 and VB1]
	that's 3, input one half and one half [referring to reservoir 2 demand, adjusting valves VA2 and VB2]
6:00	[demand pairs change at 6:11]

WL Trial #165

Time	Comment
0:00	ok sorry [no further comments during start-up]
6:00	[demand pairs change at 6:27]

WL Trial #183

Time	Comment
6:00	[demand pairs change at 6:20]
	[trial videotaped but subject made no verbal comments]

WL Trial #187

Time	Comment
0:00	oh all right [in response to experimenter's prompt to talk]
0:30	ok temperature keeps going up, adjust the heat until reservoir comes within the required range
3:30	now we adjust with a minor change of adjustment to keep the system in equilibrium [adjust heater settings]
6:00	[demand pairs change at 6:49]

WL Trial #209

Time	Comment
0:00	[demand pairs change at 6:37]
	[trial videotaped but subject made no verbal comments]

Appendix A -- Tests for Field Dependence- Independence

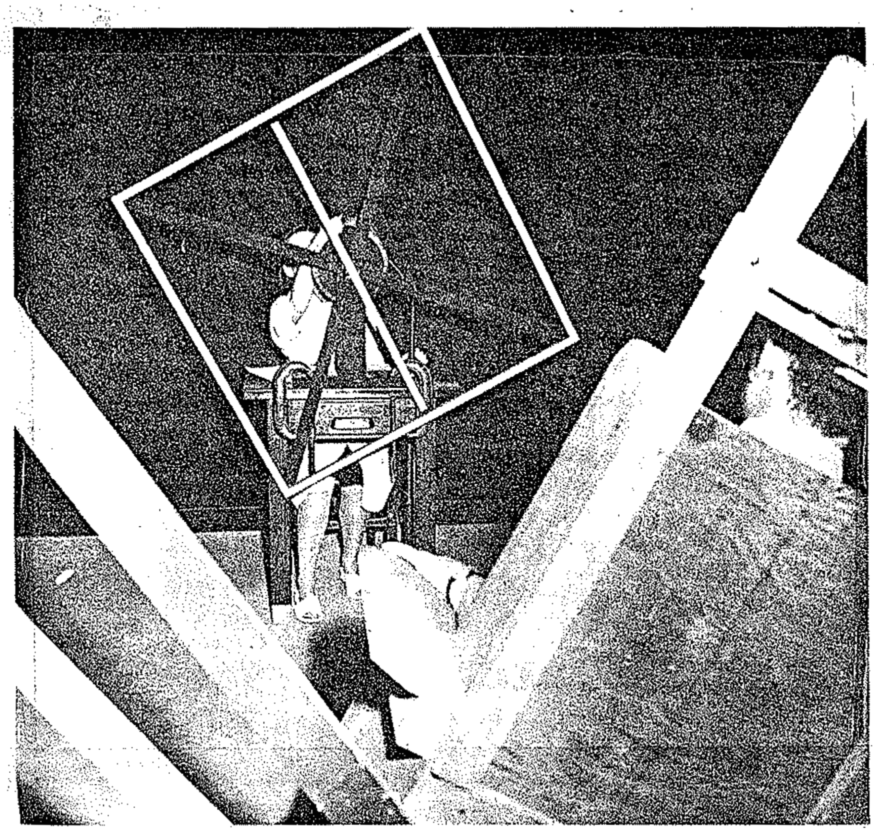

Figure A1. Apparatus for the Rod-and-Frame Test. The subject must adjust the rod to what he perceives as upright in space, while seated in a dark room (Witkin et al., 1977, p. 3)

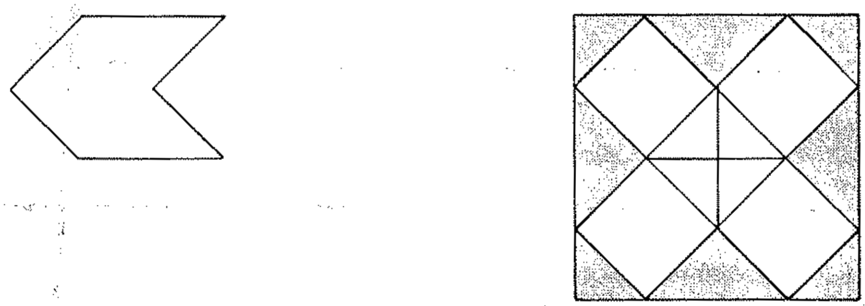

Figure A2. Sample Item from the Embedded-Figures Test. The subject must locate a simple geometric figure (on the left) within a complex design (on the right) (Witkin et al., 1977, p. 5).

Appendix B -- Test for Impulsivity-Reflection

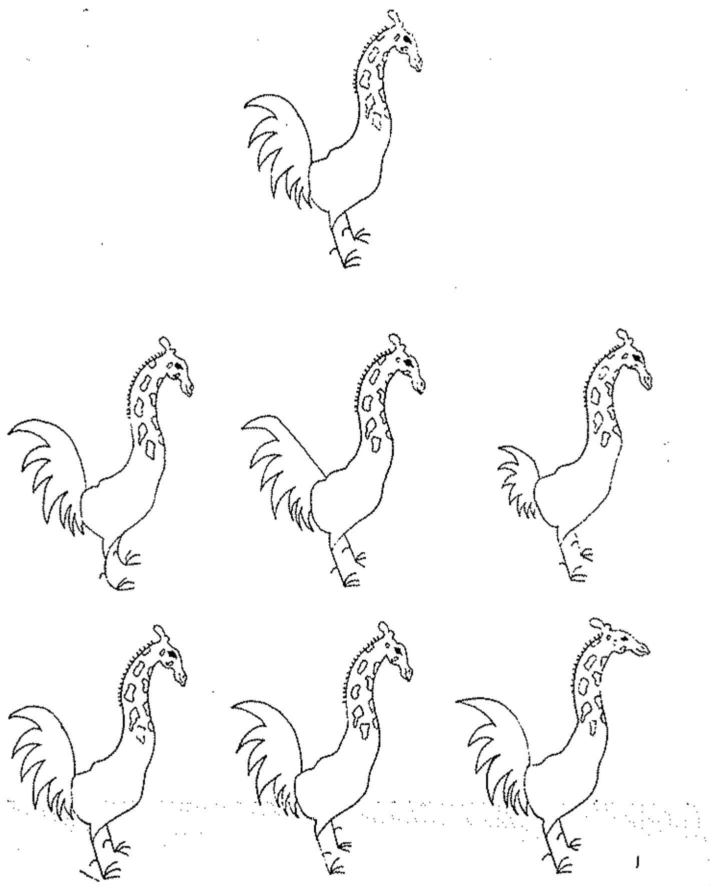

Figure B1. Sample item from the Matching Familiar Figures Test. The subject must identify a picture of an object that is identical to the standard from among a group of variants (Messer, 1976, p. 1027).