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## TOOL USAGE AND ECOLOGICAL INTERFACE DESIGN

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Field studies have shown that operators frequently use tools to “finish the design” of the interface, thereby overcoming design deficiencies. As far as we know, however, tool use has never been studied experimentally in the laboratory before in the cognitive engineering literature. In this paper, we describe an exploratory experiment that was conducted to address this issue. Two groups of participants controlled a thermal-hydraulic microworld with an ecological interface that contained physical and functional information in a single, integrated view. After an extended period of practice, each group was transferred to a different interface. One transfer interface contained the same information as the ecological interface, but across four screens that could only be viewed serially rather than in one integrated view. Another interface contained only physical information rather than physical and functional information. The results showed that tool use served four different purposes: to aid learning; to integrate information; to derive information; and to extend interface functionality. The results also provide indirect support for the ecological interface design framework because, in the transfer phase, tool use served to recover useful features that were present in the ecological interface.

### INTRODUCTION

During the mid to late 1970's, a group of researchers performed an extensive field study of American nuclear power plants in response to criticisms regarding a lack of attention to human factors in their design and operation (Seminara, Gonzalez, & Parsons, 1977). These researchers found that the operators of these plants were flexible and adaptive agents who had found many ways of overcoming design deficiencies. They were able to narrow the gap between poor design and safe, productive use.

One of the major means that operators used to narrow this gap was the physical modification of their interfaces to make them more relevant to the tasks at hand. These findings are not isolated; similar findings have been reported by Mumaw, Roth, Vicente, and Burns (in press) in the nuclear domain, and by Cook and Woods (1996) in the operating room. In addition to these field studies, Henderson and Kyng (1991) have examined user customization of software, while Hammond, Converse, and Grass (1995) and Kirsh (1995) treat agents' adapting of their environments to suit themselves from a more theoretical perspective.

This body of research is instructive as it makes a case for the significance of operator modifications as an important component of behaviour in complex sociotechnical systems. As far as we know, however, this case has never been tested in the laboratory. This paper documents one preliminary effort to do so.

### Methodology and Motivating Questions

At the outset of this research, it was not obvious how exactly to go about performing a controlled experiment on operator modifications. Three difficulties stood in our way. First, it is likely that social interactions are foundational in the

creation of, and agreement upon, functional modifications (e.g., Hutchins, 1995). Second, operator modifications are likely more frequent when operators are involved with complex tasks. Third, expertise seems to be the cornerstone of the making of modifications. Trying to create each of these conditions in the laboratory at the same time was a difficult task.

There was, however, another approach. The problems outlined above identify some of the relevant dimensions for tool use. Our approach was to pare off the dimension of social interactions, and to vary the dimensions of expertise and task complexity. This reduction was designed to make the problem more tractable and to generate results that would provide conclusions relevant to the design of more complex and representative experiments (see Vicente, 1997). This research was thus designed to build on the field studies and theoretical works that were introduced above.

It should be stressed that this was a preliminary and exploratory effort to understand the phenomenon of tool use more thoroughly, and was not guided by a well-defined theory or set of hypotheses. Instead, this research was guided by a more broad interest to understand why and how operators modify their interface, and how these modifications develop over time. An initial pilot study was designed to explore these questions (Torenvliet, 1999), which led to the experiment that is documented next.

### EXPERIMENT

#### Experimental Design

One of the challenges of addressing the research aim was in designing an experiment that was able to elicit a sufficiently large and varied amount of tool use for analysis. The design chosen is based on the work of Cook and Woods (1996) who observed operator modifications in the context of a transfer

from an old to a new interface. Our aim was to replicate these conditions in the laboratory.

The research vehicle used to create this interface transfer was DURESS II, an interactive thermal-hydraulic process control microworld driven by a simplified yet representative real-time computer model (see Christoffersen, Hunter, & Vicente, 1996). Three interfaces have been designed for DURESS II:

- The P+F interface has been designed using the principles of ecological interface design (Vicente & Rasmussen, 1992) and contains functional and physical information to support operators in both normal and abnormal situations.
- The P interface is representative of the class of interfaces that are based on piping and instrumentation diagrams, and provides only physical information, a subset of that available on the P+F interface.
- The divided P+F interface (Janzen & Vicente, 1998) provides the same information as the P+F interface, but divides this information over four windows that are only available one at a time in a serial fashion. This introduces the task of interface navigation and also requires operators to remember critical process variables while navigating between windows.

The approach taken in this experiment was to give participants about 7 hours (23 trials) of experience with the P+F interface, and then to transfer them to either the P or the divided P+F for an additional 7 hours (29 trials). Those transferring to the P interface would lose the higher-order functional information provided by the P+F interface, while those transferring to the P+F interface would keep that information while gaining the tasks of interface navigation and information integration across windows. The trials performed on the P+F interface were designed to establish a referent for participants' tool use so that the reasons for any differential tool uses that occurred across interfaces in the post-transfer phase could be inferred. Further, the experience gained by all participants both before and after the interface transfer would provide a venue for observing the evolution of their tool use. Finally, faults were distributed randomly and infrequently throughout the experiment so that any correlations between tool use and performance could be observed both in normal and fault conditions.

This design was inspired by the work of Giraudo and Pailhous (1999) who used a similar type of manipulation in their studies on human memory. They characterized this type of manipulation as perturbing the system, and were interested in observing the types of behaviour that developed as a result of the perturbation. Our design can be viewed from the same perspective. Over the first introductory trials with the P+F interface, participants would develop strategies based on the information contained in the P+F interface. After the system was perturbed by changing the participants' interfaces, it would be interesting to see how participants make modifications to cope with this perturbation.

### Participants

Previous work (Torenvliet, Jamieson, & Vicente, in press) has shown that the holist/serialist cognitive style distinction as measured by the Spy Ring History Test (SRT) is correlated with performance on the various interfaces of the DURESS II

microworld. The SRT was administered to a pool of twenty volunteer candidates from the second to fourth year mechanical and industrial engineering classes, and the six most closely matched pairs of participants were selected to participate.

### Apparatus

The DURESS II simulation runs on a Silicon Graphics Iris Indigo R4000 workstation. Verbal protocols were collected using a Sony 8mm Handycam with a head-worn unidirectional microphone. In addition, participants were given a large variety of objects that they could use to construct tools for modifying their interfaces. In particular, they were provided with: post-it notes, post-it tape flags, grease markers (to make non-permanent markings on the monitor), a notebook with both graph and lined paper, a stopwatch, a calculator, pens and pencils of various colours, an eraser, a highlighter, a magnifying glass, scissors, and paper clips.

### Procedure

Participants devoted one hour per weekday to the experiment over the three weeks of its duration, in addition to a two-hour pre-experimental session in which the SRT was administered. Participants were given two hours of training on the DURESS II process, and were introduced to the implements they could use to fashion tools. Participants were told to use these tools in any way that would make the task less difficult or their control more efficient. After this, all participants completed 23 trials on the P+F interface. At the beginning of trial 24 they were introduced to the alternate interface they would be using, and proceeded to use this interface until the end of the experiment (trial 52).

In addition to the simulator log files produced by DURESS II, a number of other types of data were collected. Participants' performance was videotaped and verbal protocols were collected for each trial. These data helped in understanding participants' tool uses in context as well as fault performance. Participants were also asked to write four control recipes over the course of the experiment, describing the strategies and steps they used to control the process. Finally, all tools created by participants were photographed for later analysis.

## RESULTS

### Tool Use

To express participants' tool use in quantitative terms, the tool uses observed over the course of the experiment were broken down into a number of categories by inferred purpose of each tool use. These categories served as the basis for generating tabular profiles of tool use for each participant. Quantitative counts of tool use and tool use variability were then generated from these profiles. The results of each of these analyses will be described in turn.

**Categories of Tool Use.** Participants were observed engaging in 18 distinct types of tool uses. These types were further aggregated into four larger categories of tool use, described below.

First of all, participants were observed using tools as an aid to learning. In early experimental trials, participants were observed using tools to help them in learning and exploring DURESS II. Some participants used their notebooks as logs to discuss various work domain characteristics and configura-

tion strategies, others used a straightedge and a magnifier to help in attuning themselves to the perceptual features of the display, and still others went through the exercise of using the grease marker to write the names of the various components on the screen. While there were many idiosyncrasies in these tool uses, they each had one characteristic in common: they had only a limited use, and so were discarded as soon as they were no longer perceived to be useful. As participants gained expertise with DURESS II and became more attuned to the visual and informational content of the various interfaces, this category of tool use faded.

Second, participants who used the divided P+F interface in the post-transfer trials were observed using tools to aid in information integration. Faced with a new interface that structured information more poorly than the P+F interface they were used to, a number of participants worked to finish (or perhaps, restore) the design back to the format they were accustomed to. For example, the divided P+F interface has one screen that contains information only at the level of the process goals. Participants were observed recording goals information in their notebooks and then referring to this information as they performed control actions and monitored the simulation on other screens. This tool use reduced participants' need to visit the screen containing goals information, and so helped them to integrate this information across all screens of the interface. To further stress the point, no participants wrote logs of this form prior to the interface transfer, and only those participants who transferred to the divided P+F interface made them post-transfer. Accordingly, it seems reasonable to conclude that this tool use was directed at the specific deficiencies introduced by the divided P+F interface.

Third, participants who used the P interface in the post-transfer trials were observed using tools to derive higher-order functional information about the system. The main design deficiency of the P interface in relation to the P+F interface is that it does not display all of the goal relevant relationships and constraints that govern the system. Christoffersen, Hunter, and Vicente (1997) observe that in the absence of these types of information, users are left to either (a) operate the system by trial and error, (b) construct rules and look for violations of them, or (c) derive this information themselves. Participants on the P interface engaged in tool uses directed to the last two of these:

- One participant used the grease marker to write values on screen to replace information contained by the P+F interface. DURESS II is operated using a network of valves to control water flows. Since either faults or operators' intent can create situations where the amount of water actually flowing through a valve is less than its setting, both the setting and flow are displayed on the P+F interface. The P interface includes the setting information, but does not include the flow information. To compensate for this, one participant derived the flows and wrote them on the screen. In a control recipe, he wrote the following explanation of this behaviour: "While the heaters 'warm up' use the grease pen to write the input and output levels for each valve beside the valves and put the sum of the inputs by the appropriate tank (i.e.,  $A_1 + B_1 = I_{n1}$ ) this will allow you to make any adjustments to the input flows quickly and efficiently."

- Two other participants were observed rethinking the task of control when transferred to the P interface. A second feature of DURESS II is that operators are required to use heaters to transfer energy to two reservoirs of water and so increase their temperature. To achieve the task goals, operators generally bring the process to a state where the amount of cold water flowing into each reservoir is equal to the amount of heated water flowing out. Consequently, the heater settings needed to achieve this state are linear functions of the amount of water flowing through the reservoirs. While the P+F interface represents the relationship between energy and flow graphically, the P interface only displays the setting of the heater and the temperature of the water. To overcome this limitation, two participants used their notebooks keep track of the flows and heater settings over a number of trials, and proceeded to derive the correct relationships. One participant codified these relationships as a pair of equations, while another drew a graph that he then used as a lookup table for heater settings.

Both of these behaviours are examples of the derivation of information to support the task of control on the P interface. Participants were also observed using this information to facilitate rule based reasoning. That is to say, if they noticed that the information they had derived did not match the behaviour of the process, participants' verbal protocols revealed they were able to conclude that a fault had occurred. Unfortunately, there was not enough data to indicate a correlation between these tool uses and an actual improvement in fault performance.

Fourth, during all phases of the experiment, participants were observed using tools to extend the functionality of the interface. For instance, to aid in making fine adjustments to the process, some participants were observed using the grease marker to indicate set-points on the heaters and valves. These 'setting-memories' allowed operators to return to these settings after the control actions had their desired effect. Other participants were observed using the stopwatch to help in timing process events. Although all interfaces included a timer that marked time from the beginning of a trial, the stopwatch was used to mark time beginning from intermediate points in the trial, obviating the need to remember or record the time at which a certain event occurred. Still other users were observed making marks on the display to help in detecting trends. It is difficult to set the input flow of a reservoir to exactly match the output flow, and so reservoir volumes have a tendency to creep slowly up or down. Some participants marked the level of the reservoir on the display to help in noticing this behaviour. Though varied, these types of tool uses all served to extend the functionality of the interface in ways not thought of by designers.

Quantitative measures of tool use. These qualitative observations of tool use were supplemented by two quantitative measures. First of all, the number of types of tools used in each trial for each participant were counted and tabulated. Figure 1 shows that there was a trend of increasing tool use during the pre-transfer phase that levelled off during the post-transfer phase. Note, however, that there was not a significant difference in the amount of tool between the pre- and post-transfer phases ( $t_{22} = 0.94$ ,  $p = 0.36$ ).

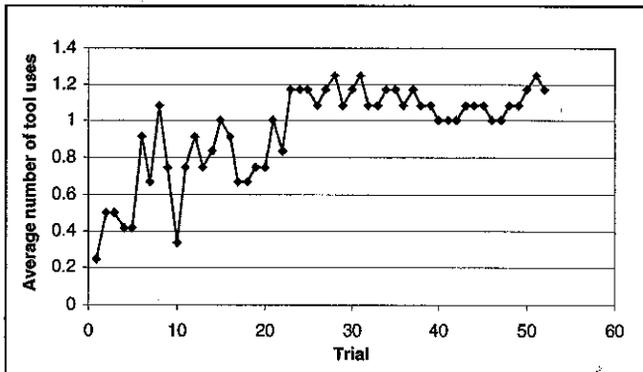


Figure 1. Average number of tool uses per trial across participants.

In order to capture the changes in tool use over the course of the experiment, a measure of tool use variability was developed. For instance, if a participant used tools A, B, and C in trial  $n$  and tools A, D, and E in trial  $n + 1$ , her variability would be scored as follows: since there was no change in her use of tool A over the two trials, this would be given 0 points; since she dropped tool B and C in the transition to trial  $n + 1$ , this would receive 2 points; since she added tools D and E in trial  $n + 1$ , this would receive 2 points. In total, trial  $n + 1$  would be given a score of 5 variability points.

Applying this measure to each of the participants' tool uses revealed that for 9 of the 12 participants, tool use variability decreased in the post-transfer phase. Even with this small sample size, this reduction almost achieved statistical significance ( $t_{16,8} = -2.02, p = .06$ ). This result indicates that participants tended to explore possible tool uses in the pre-transfer phase, but then quickly settled into stable tool use patterns in the post-transfer phase.

Finally, the total number of tool uses by category for the pre- and post-transfer phases were counted, and are shown in Figure 2. These graphs demonstrate that while the lion's share of tool uses in both phases were used to extend the functionality of the interface, the other three categories each account for an appreciable amount of the overall tool use.

### CONCLUSIONS

This exploratory research began with the motivation to understand why and how operators modify their interfaces, and how these modifications develop over time. Most significantly, it was discovered that operators use tools to attune themselves to the properties of a work domain (i.e., learning), to extend the functionality of the interface that they are given, and — in the context of a transfer to a new interface — to restore the useful functionality of the old interface. In addition, tentative evidence was presented to support the notion that these modifications will stabilize over time. Finally, this research has also been able to suggest a novel measure of tool use, tool use variability. While this research has a number of important limitations (most notably, that the participants were presented a set of tools and then were asked to look for places to apply them, as opposed to first having a problem which is then solved through tool use), we consider that this research is an important first step in working to understand operator modifications.

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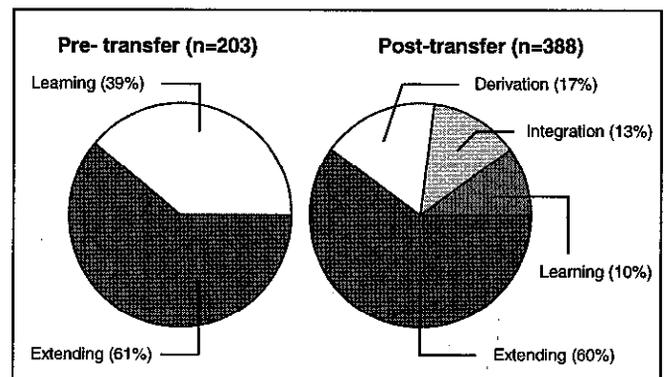


Figure 2. Percentage of total tool use, by category.