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Ecological Interface Design for Flexible Manufacturing Systems: An Empirical Assessment of Direct Perception and Direct Manipulation in the Interface

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ECOLOGICAL INTERFACE DESIGN FOR FLEXIBLE MANUFACTURING SYSTEMS: AN EMPIRICAL ASSESSMENT OF DIRECT PERCEPTION AND DIRECT MANIPULATION IN THE INTERFACE

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Dylan G. Cravens ENTITLED Ecological Interface Design for Flexible Manufacturing Systems: An Empirical Assessment of Direct Perception and Direct Manipulation in the Interface BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

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ABSTRACT

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Four interfaces were developed to factorially apply two principles of ecological interface design (EID; direct perception and direct manipulation) to a flexible manufacturing system (FMS). The theoretical foundation and concepts employed during their development, with findings related to more significant issues regarding interface design for complex socio-technical systems, are discussed. Key aspects of cognitive systems engineering (CSE) and EID are also discussed. An FMS synthetic task environment was developed, and an experiment was conducted to evaluate real-time decision support during supervisory operations. Participants used all four interfaces to supervise and maintain daily part production at systematically varied levels of difficulty across sessions. Significant results provide evidence that the incorporation of direct perception and direct manipulation in interface design produced an additive effect, allowing for greater support for the supervisory agents.

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INTRODUCTION

Technological advances in computational and processing power afford designers the potential to leverage users' powerful perceptive and pattern recognition capabilities to improve the quality of overall system performance. One use of this continuously evolving computational power is developing and utilizing autonomous systems that either replace or complement human operators (Bennett, 1993). An alternative is to develop graphic displays to aid in decision support. Graphical displays can facilitate performance by assimilating relevant data, providing more apparent visualizations of work domain constraints, and allowing for greater conceptual understanding of abstract relationships (Bennett, 1993). However, utilizing this potential to build displays that support effective decision-making and problem-solving in today's complex socio-technical systems has been underutilized on a regular basis. Interfaces are often not optimized for the human user (Hall, Shattuck, & Bennett, 2012), producing unnecessary cognitive strain, relying on faulty and inadequate schema, and forcing users to adapt needlessly to an insufficient and over-complicated system.

Cognitive systems engineering (CSE; Norman 1986; Rasmussen 1986; Rasmussen, Pejtersen, and Goodstein 1994; Vicente 1999) provides an overarching framework for the analysis, design, and evaluation of effective computerized decision support. Ecological Interface Design (EID; Bennett & Flach, 2011a; Hall et al., 2012;

Rasmussen & Vicente, 1989, 1990; Vicente & Rasmussen, 1990, 1992) is a compatible framework focusing on the development of principles for effective display and interface design (Hall et al., 2012). Over the past 30 years, the CSE/EID approach has been applied to a wide variety of work domains. Over 80 percent of empirical evaluations have provided statistically significant performance advantages favoring the CSE/EID approach relative to traditional interface design approaches (Bennett & Flach, 2019).

Despite these observations, only a handful of preliminary attempts have been undertaken to apply the CSE/EID approach to the work domain of flexible manufacturing systems (FMS; Benson, Govindaraj, Mitchell, & Krosner, 1992; Dunkler, Mitchell, Govindaraj, & Ammons, 1988; Krosner, Mitchell, & Govindaraj, 1989). We have initiated a research program to do this, developing a representative simulation of an FMS to provide a synthetic task environment (STE) for evaluation. We initially developed both a standard and ecological interface and have conducted two experiments to evaluate them. In the present study, we describe the evaluation of four alternative interfaces that were developed with and without the application of two fundamental principles of ecological interface design.

1.1 Cognitive Systems Engineering/Ecological Interface Design

Cognitive systems engineering (CSE) is an integrative, multidisciplinary approach emphasizing human cognitive processes for advanced sociotechnical systems. In terms of interface design, CSE does this through the provision of general concepts and analytical tools (e.g., decision ladder, abstraction, and aggregation hierarchies) that can be applied to identify important characteristics of a work domain. The primary goal of CSE is to design *adaptive* systems, allowing for human expertise and potential for productive cognitive processing to be adequately leveraged (Flach et al., 2017) during times of uncertainty within a dynamically and rapidly changing environment (Flach, Bennett, Stappers, & Saakes, 2005). The subgoals of CSE include the following: to understand domain constraints (i.e., the regularity in a domain or characteristics of the underlying work domain), the decisions that need to be made, the information that is relevant to these decisions, and the fundamental modes of human behavior which need to be supported.

Ecological interface design (EID) is a complementary framework to provide effective decision-making and problem-solving support through transparent interfaces for complex, real-time, and dynamic human-machine systems (Bennett & Flach, 2011b). EID differs from traditional interface design approaches like user-centric or task-centric design that focus solely on the end user or a specific task. Instead, Ecological Interface Design focuses on the work domain, with the goal of faithfully discerning and representing the constraints and complex relationships in a work environment. The design of decision-support for complex human-machine systems through EID is framed contextually within a *triadic* model of semiotics (Peirce, 1931-58). Informed decisions about an interface (medium) design can only be made within the context of both the work domain (situations) and the cognitive agent (awareness; Bennett & Flach, 2011b). The EID approach focuses on the relational invariants (pragmatic constraints) between agent/work domain interaction. By understanding the deep structure of the work domain, designers can explicitly represent the meaningful constraints (and their corresponding state variables) through representational aids to shape accurate schema (Flach et al., 2005; Flach et al., 2017). The goal of EID is to produce a virtual ecology (Rasmussen et al., 1994) to map these relational invariants through organizational and pattern-specific representations. This, in turn allows more of users' cognitive resources to be devoted to higher cognitive processes such as problem solving and decision making and bypass human working-memory limitations to improve performance and overall system stability for both anticipated and unanticipated events in a complex work environment.

Three global principles of ecological interface design have been developed to ensure the effective mapping of functional invariants within a work domain (Bennett & Flach, 2011b): direct perception, direct manipulation, and visual momentum. The principle of *Direct Perception* involves the design of a virtual ecology where functional system invariants are mapped into analogical representations in the interface (Rasmussen & Vicente, 1990). *Direct Manipulation* requires the development of system controls that maintain an intact perception-action loop. The designer must create an artificial ecology within the virtual environment that maps the functional system constants to the interface (Rasmussen & Vicente, 1990). *Visual Momentum* (Woods, 1984; Bennett & Flach, 2012) involves applying various techniques that allow the user to pick up the necessary information presented within the interface through effective navigation between screens and the location of critical information within screens.

The goal of these three principles is to translate the agents' activities from cognitive (requiring limited capacity resources) to predominantly perceptual-motor (with near unlimited capacity; Bennett, Posey, Shattuck, 2008). In the following section, we describe these principles of EID in more detail and provide concrete examples of their application to the work domain of FMS.

1.2 Direct Perception

Gibson (1966, 1979) introduced the theory of direct perception, emphasizing organisms interacted directly with their environment. Gibson believed that perception is not part of a psycho-physical system (i.e., visual system) or an inferential process. Instead, sensory perception directly results from the coupling between the information available in the environment (e.g., the perceived object, affordances) and the agent (Chemero, 2009). Conventionally, this knowledge (perception) has been conceived to involve higher-level processes to compute mental images by collecting and assimilating ambiguous environmental cues (Bennett & Flach, 2011a). The theory of direct perception emphasizes that an organism interacts directly with their environment with no need for processes that transform or supplement incoming data. Gibson argued that in real life, humans are not passive observers of isolated objects, but rather agents interacting and engaging with entire scenes, while navigating through them. Because of this, the eye receives complex and dynamic patterns of light bouncing off and being redirected from a variety of sources as we move through time and space. As such, people can directly perceive meaningful properties of the environment, or affordances, by collecting, discovering, and associating environmental cues without having to resort to mediating inferences, experiences or representations. Therefore, agents guide behavior by taking advantage of invariant optical relationships to bypass unnecessary cognitive demands and develop direct associations (Bennett & Flach, 2011a).

In EID, the term direct perception is heavily inspired by the work of Gibson. Direct Perception (within the context of EID) pertains to the perceived state of the system, moderated by the quality of mappings of relational invariants of the work domain, which allows relevant affordances for actions to be easily distinguished by agents. (Bennett & Flach, 2011a; Hall et al., 2012). Thus, the display should be designed to provide visual information that directly specifies the state of the work domain and presents patterns to specify future outcomes (i.e., goal achievability, future problem-states; Flach et al., 2005; Smith, Bennett, & Stone, 2006).

The success of implementing direct perception within an interface depends on two different sets of mappings. The first set, *content mapping,* refers to the relationship between the display and the work domain (Talcott, Bennett, Martinez, Shattuck, & Stansifer, 2007). The visual limitations of a display and informational content encoded through graphical representation must constraint-match those in the work domain (i.e., the visual evidence should map directly onto affordances of the work domain). The second set of mappings, *form mapping*, involves the relationship between the visual properties within the graphical representation of the work domain and the perceptual capabilities and limitations of the agent (Talcott et al., 2007). Form mapping represents the extent to which 1) representations allow the human to recognize information regarding the problem space (i.e., the affordances of the work domain presented through the interface), and 2) the observers' learned ability to recognize the appropriate response based on the patterns presented within the interface. The quality of these mappings and the degree to which direct perception is achieved determines the extent to which the state of the work domain can be easily perceived, and the appropriate actions can be taken (Hall et al., 2012).

1.3 Direct Manipulation

Gibson (1966, 1979) emphasized that the foundation of a dynamic and continuous perception-action loop was instrumental in an agent's successful navigation/interaction through their environment. This concept translates equally into interfaces that provide a visualization of the states/constraints of the work domain (Bennett et al., 2008). Direct manipulation refers to the execution of control input. The desired operations are completed through the virtual manipulation of icons/objects within the display rather than through an abstract computational medium (Hutchins, Hollan, & Norman, 1985). Direct manipulation allows for the use of high-capacity sensorimotor control by ensuring spatial-temporal connectivity through an intact perception-action loop (Rasmussen, 1986; Vicente & Rasmussen, 1988; Vicente, 1999; Bennett et al., 2008).

Furthermore, direct manipulation interfaces create a sense of immersion (a qualitative feeling of engagement; Hutchins et al., 1985). The operator experiences an immediate sense of control over intentions and goals within the work domain by manipulating metaphorical or analogical objects within the interface (Shneiderman, 1987; 1993). Interfaces should allow the operator flexibility to navigate within the problem space, actively test hypotheses, and experiment with the environment to provide immediate feedback. Shneiderman listed several attributes of these direct manipulation interfaces, identifying them through their continuous representations, characterized by rapid, incremental, reversible operations (Shneiderman, 1982, p. 251), whose impact is immediately transparent to the operator. By supporting an intact perception-action loop, the interface can support exploration for decision-making purposes and become an essential element for discovery to facilitate a greater understanding of abnormality within the work system (Bennett & Flach, 1992).

1.4 Visual Momentum

Visual momentum refers to the agent's ability to abstract and consolidate information presented across displays with the explicit objective of increasing the agent's *cognitive coupling* with the work domain (Woods, 1984; Bennett & Flach, 2012). As a result, the cognitive effort required to extract and incorporate information following a transition either within a single display, within a screen, or between multiple display screens is inversely proportional to the quality of visual momentum supported by an interface. (Woods, 1984; Woods & Watts, 1997; Hall et al., 2012). High visual momentum is characterized by continuity across the transition, where the expectancies formulated within one display (or one section of a display) are realized within the second display (or second section of the same display), allowing for rapid and near-effortless comprehension of data (Woods, 1984). Low visual momentum will obfuscate data. Woods compares low visual momentum to be "like a bad cut in film editing" (1984, p. 231). Here, the transition is obvious; its presence is distracting, causing a breakdown in the agents' attentional processing due to a mismatch in man-machine coupling (Woods, 1984).

Visual momentum can be viewed as a three-tiered hierarchy. At the highest level (*workspace*) of interface design, the principle of visual momentum focuses on providing resources that support navigation (i.e., the "smoothness" of multi-screen transitions). The workspace level provides the agent with information regarding where they are and where they might want to go by perceptually or cognitively orienting the agent to the particulars of their new destination (Bennett & Flach, 2012). An interface with high degrees of visual momentum concerning the workspace would provide spatial metaphors such as landmarks or navigation bars to delineate location (via direct perception, e.g., "you are here"). These features afford a visual "preview" of potential destinations the agent can navigate between (through direct manipulation, e.g., traversing a site map and selecting a hyper-link). The next tier of the visual momentum hierarchy focuses on the intra-screen transition (i.e., between multiple displays within a screen, *view* level). Bennett, Bryant, and Sushereba (2018) describe a system in which the positioning of the mouse over a single piece of information in one display produces a highlight effect (increasing perceptual salience) of all functionally related information that is available within the interface. The last tier includes structures within one display (i.e., the visual elements of the display itself, *form* level; Bennett & Flach, 2012). This level focuses on providing effective visual (i.e., spatial) structures that guide successive fixations of the eye, allowing the representation of various information in the display that matches the work domain with the same relative importance. The constraints resulting from limited display real estate and necessary information output typically associated with today's complex systems provide a distinct challenge; finding the information needed to make timely decisions regarding nonoptimal states becomes a challenging task.

Summary. EID principles (i.e., direct perception, direct manipulation, visual momentum) can be used to build interfaces that provide more effective decision-making and problem-solving support. The principle of direct perception guides the development of a virtual ecology that faithfully represents the relevant constraints of the work domain. The principle of direct manipulation guides provides space-time signals through controls that map specifically to required work domain inputs (Bennett & Flach, 2011a). Finally, the principle of visual momentum guides the development of interface resources that improve the participants' ability to extract information from displays and integrate information across displays (Woods, 1984).

In combination, direct perception and direct manipulation provide broad support for problem-solving and decision-making (Flach et al., 2005) by combining sophisticated and dynamic graphical representation with the agent's powerful perceptual and pattern recognition potential. The principles underlying EID allow for the development of interfaces that assist with agent's ability to both safely and efficiently 'see' and 'explore' complex systems for their possibilities for action through the direct comparison between consequences and intentions (Flach et al., 2005; Flach et al., 2017). When explicit action is not present, however, the interface should assist the agent in understanding the system state, allowing for the agent to discover potential action through hypothesis testing (Flach et al., 2005), providing constructive feedback for learning about the novelty currently represented (Flach & Voorhorst, 2019).

The CSE/EID approach can be contrasted to one which is 'prosthetic' in nature: "One approach often adopted implicitly or explicitly is to design support systems as prostheses-replacements or remedies for deficiencies." (Roth, Bennett, & Woods, 1987, p. 479). Automation is a prime example of this prosthetic approach. Rather than supporting the agent, the explicit goal of automation is to use computational resources to replace the human. In the upcoming sections, we discuss these issues in automation.

1.5 Flexible Manufacturing Systems

Due to the competitiveness within the manufacturing industry, designing systems in both a flexible and adaptive manner that allows for efficient and timely processing is necessary if corporations are to succeed in today's variable socio-economic climate (Rasmussen et al., 1994). Flexible manufacturing systems (FMS) have been proposed as a means to do just this. Flexible manufacturing systems are computerized production systems, characterized by a multi-functional network of machining centers and storage buffers interconnected to material management and conveyor system capable of simultaneously manufacturing multiple product types (Mitchell, Govindaraj, Dunkler, Krosner, & Ammons, 1986; Ammons, Govindaraj, & Mitchell, 1988; Benson, Govindaraj, Mitchell, & Krosner, 1989). Flexible manufacturing systems attempt to augment traditional production facilities (e.g., assembly lines) with computerized technology (e.g., automated control). In turn, this allows FMS to be adaptive and responsive to the quickly changing dynamics of variable circumstances (e.g., market conditions, customer requirements, business objectives) and performance complications (e.g., automated scheduling error, hardware malfunctions, resource limitations; Benson et al., 1989).

1.5.1 Automation and Human Supervisory Control

Most research within FMS seems to forgo the use of human supervisory control, regardless of the results which substantiate human supervision as leading to consistently superior performance when compared to fully automated control systems (Dunkler et al., 1988; Nakamura & Salvendy, 1988; Tabe & Salvendy, 1988; Kondakci & Gupta, 1991). Research within FMS tends to disparage supervisory control as a necessary byproduct of an incomplete and imperfect automated system, stipulating that a supervisory presence is required only to provide back-up, ensuring operational success, instead of being one-half of an equally coupled dynamic (Mitchell et al., 1986). This attitude can be seen repeatedly in research attempting to bridge the gulf of autonomous execution through the complex syntax of rule-based algorithms.

While increasing automation is a sensible decision, the effectiveness of rule-based control models is conditional on the attributes, assumptions, and operations of the system (Mitchell et al., 1986). Modelers' lack of domain-specific information and the relative inaccessibility of appropriate resources can hamper the success of these analytical models. Expert systems emerged to compensate for these inadequacies. However, they, too (expert systems), are limited by the capabilities of their inferential engines (Dunkler et al., 1988; Sanderson, 1989). Furthermore, due to the dynamical state of complex systems like FMS, it is difficult for analytical models (e.g., FMS schedulers) to predict and account for novelty in the fast-changing environment, often impeded by uncertainty. As such, these fully automated schedulers are unable to provide creative problem-solving solutions when novelty is encountered (Mitchell et al., 1986).

As stated by Dunkler et al. (1988) on manufacturing facilities, the *dynamical* states of FMS reinforce the necessity of the supervisory control paradigm because these fully automated flexible manufacturing systems are, in fact, flawed. The continued presence of an agent-based supervisory role is not only advocated but should also be afforded the same priority within FMS as the automated scheduling system. Dunkler et al. posit three tenets that coincide with this goal. First, supervisory systems should be designed to provide a sensible, transparent division of responsibilities that unambiguously explain the agent's role and position. Second, the agent's responsibility should be presented explicitly to the fullest capabilities of the system's hardware and software. Third, the automatic processing should be adequately integrated to allow for supervisory monitoring and ad hoc intervention (Dunkler et al., 1988).

The goal should be to integrate human-in-the-loop control and enhance graphical interfaces for real-time recognition and intervention when non-optimal situations arise. Through these tenets, the human supervisor can monitor system progression, adjust parameters, and compensate for any scheduling and automation deficiencies, improving the system's overall performance and efficiency (Mitchell et al., 1986). Therefore, the focus should be on providing real-time, ecologically-valid support systems for the supervisory agent, thus complementing the views of Dunker et al. (1988).

1.5.2 Flexible Manufacturing Systems Simulation

The simulation described by Dunkler et al. (1988) is a representative example of a flexible manufacturing system. We developed a version of this simulation to serve as a synthetic task environment (STE) for interface evaluation. Our simulation is very similar to Dunkler et al. (1988), with some minor exceptions.

The system performs machining operations on a virtual family of engine parts (seven part-types, labeled A-G). Each part type varies in the total quantity needed to meet daily demands (ranging from 3-30) and in the specific number of required operations (1-3, in sequence) to be completed. Each of the three operations differs in completion length per part type. The daily shift production goals for each part type are derived from an aggregate part type/processing times table found in Dunkler et al. (1988). The system automatically moves parts between subsystems (e.g., arrival buffer, load/unload stations, machining centers, batch operation, overflow buffer, work in progress buffer), performing various production activities (e.g., positioning, machining operations, heat treatment). The automated scheduler utilizes a first come, first serve (FCFS) sequencing algorithm. This simulation focuses on the role of real-time supervisory control within the FMS system (Dunkler et al., 1988). The FCFS algorithm is an optimal choice as its base functioning provides no automated heuristics to aid in supervisory decision-making. Supervisory control functions include monitoring and refining the automated scheduling processes, ad hoc intervention including part expedition (changing the production schedule established by the automation), work in progress (WIP) buffer capacity adjustment, and machining center cell operation change.

1.6 EID in Flexible Manufacturing

This section focuses on applying the abstraction hierarchy during the initial stages of the FMS work domain analysis. We utilize this modeling effort to inform specific design choices for an ecological interface to support the FMS operator in completing supervisory duties.

The *Abstraction Hierarchy* (Rasmussen, 1983, 1986) serves as an analytical tool, consisting of models for both physical and functional systems to categorize information and the inherent relationships between levels of information for the development of complex work domain representational aids (Bisantz & Vicente, 1994). The abstraction hierarchy provides five independent levels (categories) of information to identify and integrate a work domain's goal-relevant constraints and the inherent relationships between them (Bennett & Flach, 2012; Vincente & Rasmussen, 1992) that are necessary for the proper functioning of a controlled system.

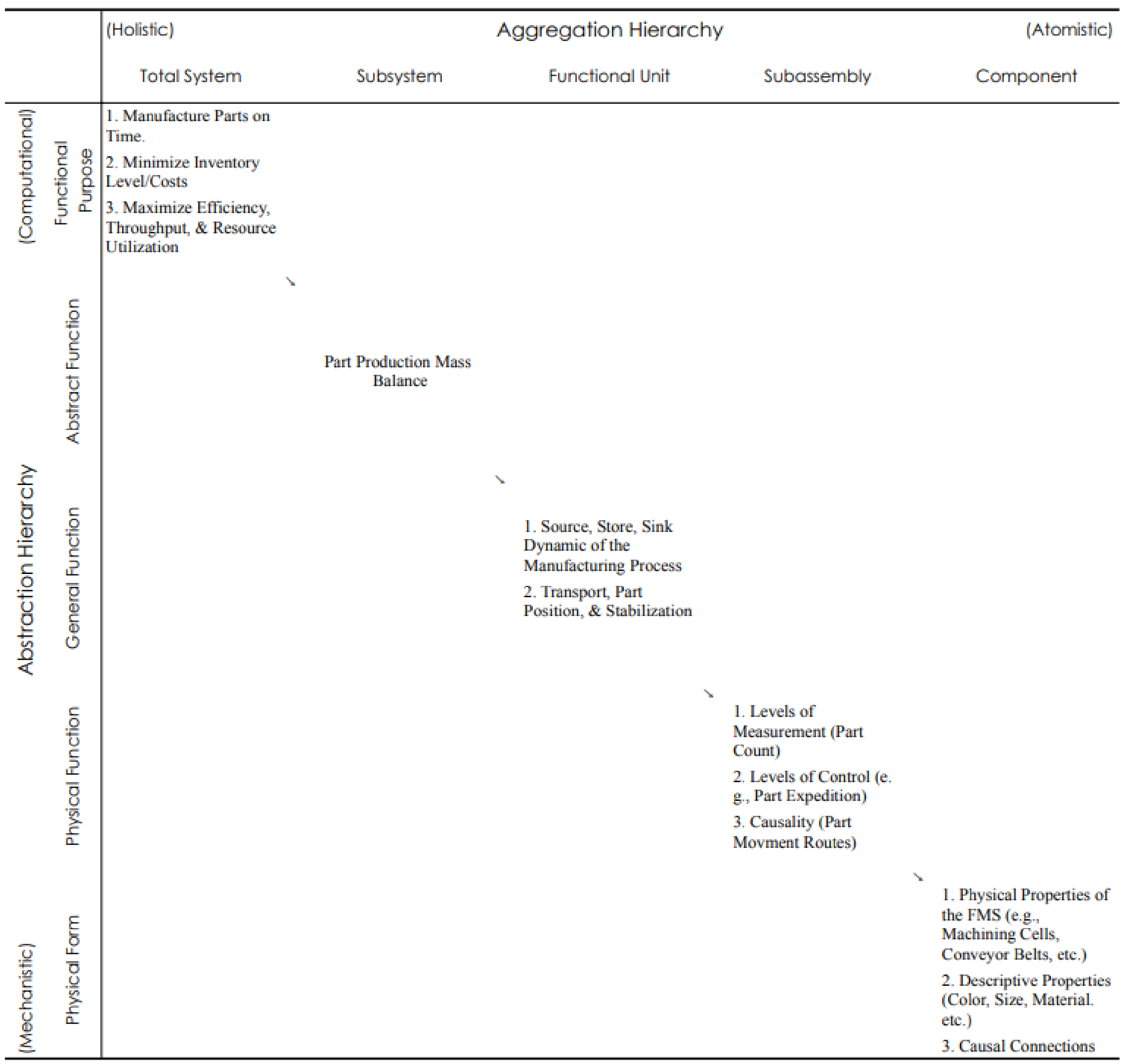
The abstraction hierarchy frames domain information in terms of structural 'means-end' relations with goals (i.e., ends) to be achieved and physical/system resources (i.e., means) used to achieve them (e.g., Naikar, 2013; Bennett & Flach, 2011a). Global invariants should be mapped to the highest levels of the abstraction hierarchy, while display elements should be mapped to the lower levels to provide the most effective means of communicating with the user. In complex socio-technical systems, visual representations (through direct perception) provide a basis for allowing the operator to perceive how their actions relate to higher-level functions and lower-level relationships. Through this method, the designer can direct attention to critical information (global invariants) while simultaneously providing data for specific variable states (display elements; Bennett & Flach, 2011a). A work domain analysis was performed on the FMS STE utilized by Dunkler et al. (1988). Constraints were first identified and then incorporated into an ecological interface.

The *Aggregation Hierarchy* is a complementary analytical tool. The aggregation hierarchy provides a description of the work domain in terms of nested part-whole relations (Bennett & Flach, 1994). This allows the work domain to be described at varying levels of resolution (holistic to atomistic; Bennett & Flach, 2011a). Modeling the constraints of a work domain through both of these analytical tools is necessary due to the inherent complexity of work domains. The outcome of these analyses specifies the affordances of the work domain, specifically the required information content and the context in which it should be used to support the agent when changing their attentional focus (Bennett et al., 2008; Bennett & Flach, 2011a).

The Cognitive Systems Engineering/Ecological Interface Design process was applied to our initial simulated FMS experiment (Jackson, 2020). The abstraction/aggregation hierarchy (Figure 1.1) will now be described regarding the interface developed.

Figure 1.1

Abstraction/Aggregation Hierarchy of a Flexible Manufacturing Systems



1.6.1 Direct Perception

As previously described, direct perception within the interface is achieved through the development of a virtual ecology that directly specifies invariant constraints allowing the agent to pick up task-relevant information "without the mediation of memory, inference, deliberation, or any other mental processes that involve internal representations" (Zhang, 1997, p. 181), so that "the end product of perception is the end product of the whole problem-solving process" (p. 187).

Functional Purpose. The highest level of the abstraction hierarchy corresponds to the work domain's goals, purposes, and constraints. This level corresponds to meeting specific production goals and associated priorities (i.e., part production quantity for each part type to meet daily shift demands). The user's ultimate tasks/goals include minimizing part tardiness and inventory levels, maximizing efficiency, throughput, and resource utilization (see Figure 1.1). This level of the abstraction hierarchy can also be conceptualized as the level at which interactions with the external world occur. In this instance, production goals represent the expressed interests of the manufacturing facility to complete a prespecified number of parts for their customer base.

There is a tradeoff of benefits and costs in meeting (or not meeting) these goals and their corresponding priorities. For example, a high priority is to minimize the occurrence of tardy parts (to meet the expectations of the customer base). If the occurrence of tardy parts is inevitable, deciding which part(s) to prioritize based on their respective time-to-complete and the earning of the part post-sale constitutes a significant trade-off. Another trade-off is the need to have sufficient raw materials for part production while simultaneously minimizing extraneous levels to avoid additional costs associated with high inventory levels. Finally, there is a general need to maximize the efficiency of the production process (e.g., maintain high throughput and resource utilization).

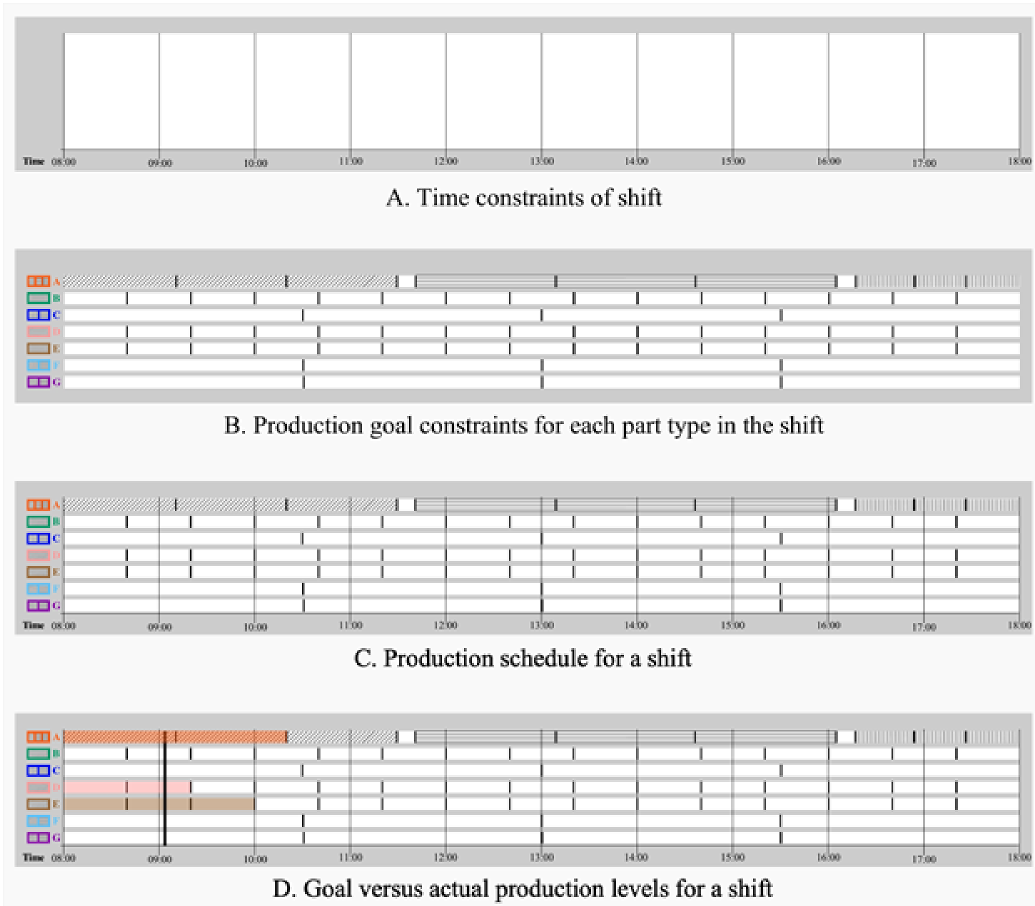
The ecological display (i.e., Production Overview Display; see Figure 1.2) was designed to represent the FMS constraints at this level and provide real-time decision support for the operator. The production goals for a 10-hour shift are specified directly using analogical representations in a display located at the top of the screen. The time constraints associated with achieving these production goals are represented explicitly in Figure 1.2a, with the x-axis of the display divided (and labeled) in 1-hour increments.

The dynamic (per simulated shift) production goals associated with each part type are the second set of constraints that must be specified at this level. Figure 1.2b illustrates the display elements which correspond to these constraints. Each part type (i.e., Part A – G) is represented as a color-coded display icon occupying a row on the y-axis. The total number of completed parts required during a shift is represented as a segmented bar graph with the number of segments per row expressing the daily demand for each part type. The analogical representation (i.e., the length of a bar graph segment) represents the amount of time allocated to an individual part if production goals are to be met.

Daily production goals are superimposed over the representation of the time constraints associated with a shift (Figure 1.2c). Together, these two sets of static representations (segmented production goals and 1-hour shift divisions) directly specify a shift's production schedule.

Figure 1.2

The Production Overview Display



Abstract Function. The second category of information in the abstraction hierarchy refers to criteria relating to priority measures and reading process/production values. The abstract function level can be conceptualized as the level that reflects the intended proper functioning of a system according to the natural or societal laws that govern it. This description often involves the expected flow of energy, information, or resources through the system. Within the FMS STE, this category pertains to the flow of raw material into the system, the completion of machining operations on these materials, and the exiting of finished parts out of the system. This level also refers to the intended proper functioning of the system or the timely execution of the shift's production schedule for each part of our FMS system.

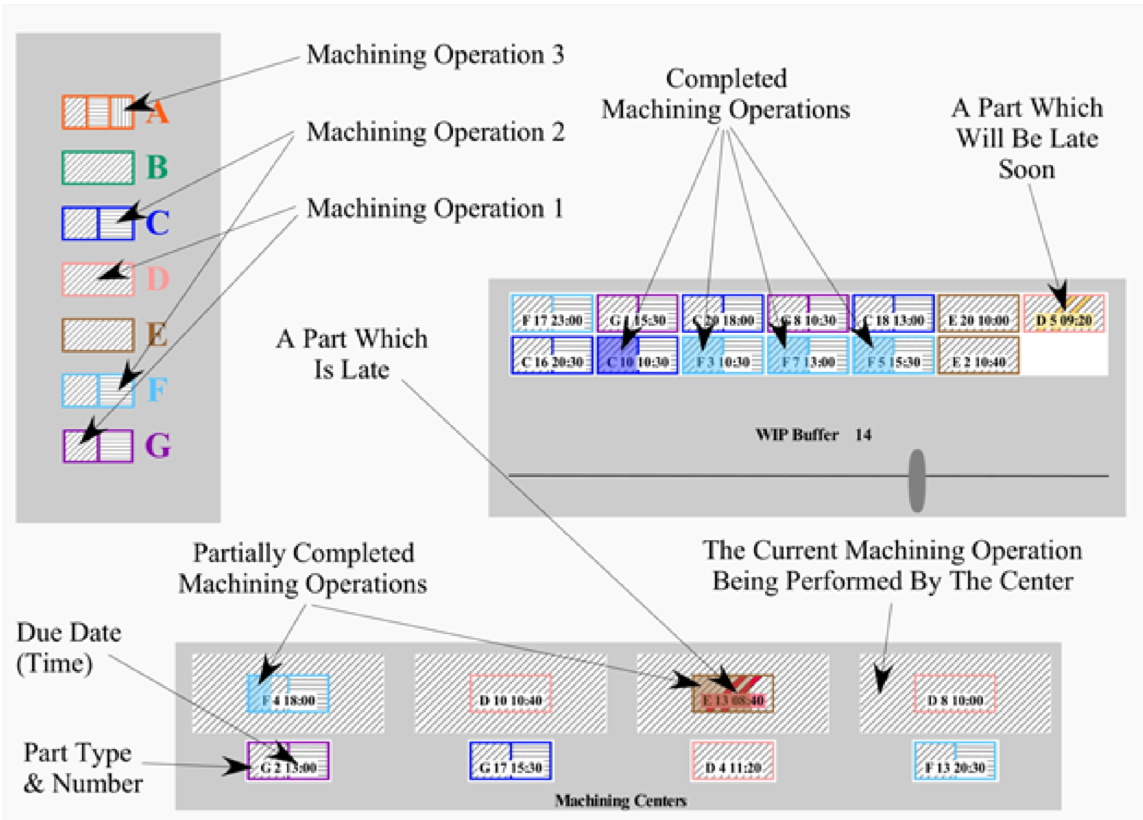
Information pertaining to the abstract function of the abstraction hierarchy is specified directly in the analogical display (refer to Figure 1.2d). As the parts are completed, bar graph segments representing each part type are filled in (from left to right). Shift time was measured as a vertical black bar that, in conjunction with the current time of the scenario, transitioned from the left to right side of the overview display. Abstract functions are presented through the location of this vertical black bar on the x-axis as it corresponds to the current time of the shift, with visual elements of this display working on specifying temporal deviations between scheduled (i.e., goal) production level and true production level (i.e., whether the agent is on-par with meeting daily production goals at their current production rate). Gaps of unfilled bar graph segments to the left of the vertical black bar represent under-production (see production level of part B in Figure 1.2d) at that stage of the shift. This representation allows the agent to quickly identify the relative duration of time left in the scenario and judge overall progress in meeting daily shift demands - from a part-whole perspective.

Generalized Functions. The third category of information within the abstraction hierarchy concerns the general work activities and functions the system must accomplish. General functions of the FMS system include the source (bring parts into the system) store (hold parts in various stages of completion), sink (remove parts from the system), dynamic, transport (move parts through the system), part position, stabilization (e.g., load/unload stations), and production process (completion of various machining operations and heat treatment). The system components capable of delivering these general functions are simultaneously visible yet visually segregated in the virtual ecology through dark-colored background mattes (refer to Figure 1.4). Arrows present the abstract couplings necessary to complete a part, detailing intermediary connections between the different system components (e.g., arrival buffer, overflow buffer, and machining centers).

Physical Function. All higher levels of the abstraction hierarchy are concerned with the functional properties of the work domain. Physical Function is the first level of the abstraction hierarchy referring to physical properties. The fourth level refers to physical activities in work, physical processes of equipment. Physical function constitutes the level of measurement (e.g., part counts), control (e.g., expediting a part), and causality (routes to accommodate part movement). Physical function is used to produce a description of the physical objects of the system, their relevant functional properties, and any coupling between them. There are a wide variety of physical elements in the FMS system. The different buffer types and how many parts each of them holds, individual parts and operation requirements for each, machining operations and operation lengths, etc., constitute physical activities or processes within the FMS work domain and need to be described at various levels of granularity. Figure 1.3 provides a detailed description of individual parts, their critical properties, and the interface conventions developed to represent these properties. The base level of representation for each part is a rectangular graphical icon. The number of different hatching patterns on a part type informs the agent of the operations required to complete that part type. The patterns are also present on the machining centers to inform the user of the currently selected operation for each machining center. Each part also contains an alpha-numeric label (e.g., F 17) to differentiate it from other parts of the same type and a discrete color code to differentiate part types from one another.

Figure 1.3

Representational Conventions for Individual Parts



Each part was partitioned into a maximum of three sections, visually specifying the number of machining operations (1, 2, or 3) required for each part to be completed (see upper left of Figure 1.3). In addition, each segment has alternative perceptual fills (cross, horizontal or vertical hatching), which specify the type and serial order in which the operations need to be performed.

A transparent fill inside each segment specifies the current status of the various machining operations. A partially filled segment is an analogical representation of the percentage of completeness for an operation in progress (e.g., Part E 11, Figure 1.3). A filled segment represented an operation that had been completed.

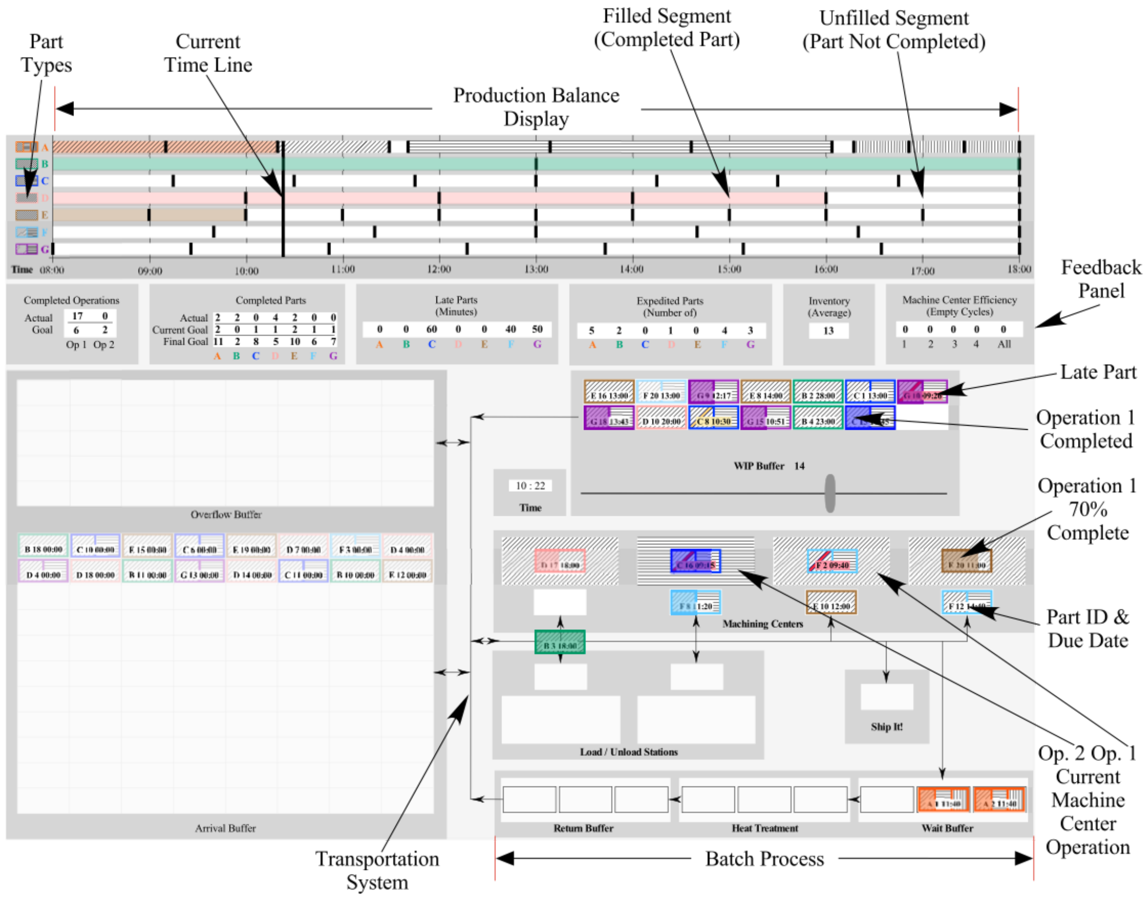
The scheduled completion time for a part is specified both analogically (see the previous discussion) and alpha-numerically (time label to the right of the part label). In addition, a salient perceptual cue is drawn (two yellow stripes superimposed on a part's icon, e.g., Part D 5) when a part was near *tardy status* (i.e., 20 scenario minutes) or when the part officially became tardy (two red stripes superimposed on a part's icon, e.g., Part E 13). The Ecological interface incorporating constraints outlined in the abstraction hierarchy and corresponding design choices can be seen in Figure 1.4.

Physical Form. The last level of the abstraction hierarchy details that of physical appearance, location, and configuration. For example, when manufacturing a product must adhere to strict specifications with minimal tolerances for error concerning physical properties (e.g., shape and size). In the case presented, the machining center for an internal combustion engine must be manufactured to have precise physical measurements if the part is to function as intended.

Little to no information pertaining to the level of physical form is represented in these displays. Bennet and Flach (2011b) state that this category of information is not particularly important for displays designed for effective control, especially for those controlling a system remotely (i.e., supervisory control). Representation of information at this level would be a priority to an operator or technician whose job involved manual physical system activities (e.g., valve adjustment/repair).

Figure 1.4

Graphical Interface for STE Utilizing CSE/EID Principles



1.6.2 Direct Manipulation

The user directly manipulated objects in the interface to execute three different types of control input: part expedition, WIP buffer capacity adjustment, and machining center cell operation change. To expedite a part (i.e., to change the order of processing that the automated scheduler had scheduled), agents employed point-click-drag mechanics using their mouse to select and maneuver a part to its desired location. To change the number of parts that could be stored in the WIP (ranging from 0-21), users point-click-dragged an adjustable slider bar to control the WIP capacity size. To change machining operations, the user point-clicked the desired machining center cell. Each click would adjust the machining center cell to cycle from the current operation (e.g., 1) to the next operation (e.g., 2) sequentially before restarting (i.e., 1, 2, 3, 1...). Machining center cells were cycled independently of one another. Figure 1.4 shows machining center cells 1, 3, and 4 (from left to right) in operation 1, indicated by the machining center cell's diagonal hatching.

1.6.3 Visual Momentum

Support for the highest level of visual momentum (i.e., resources that support navigation between screens) is unnecessary (due to the use of a single-page display). All system-related information is located on the same screen and is therefore immediately available for viewing. This is an example of the overlap design technique described by Woods (1984). Information derived from the abstraction hierarchy (e.g., goals, functions, and physical components) is presented in a single, integrated viewing context. The user is not required to navigate between screens to obtain critical information, remember said information, navigate back, and only then consider the meaning of this critical information in the original viewing context. Visual momentum is high: a continuous graphical explanation of ongoing events in the FMS system is provided in a single viewing context.

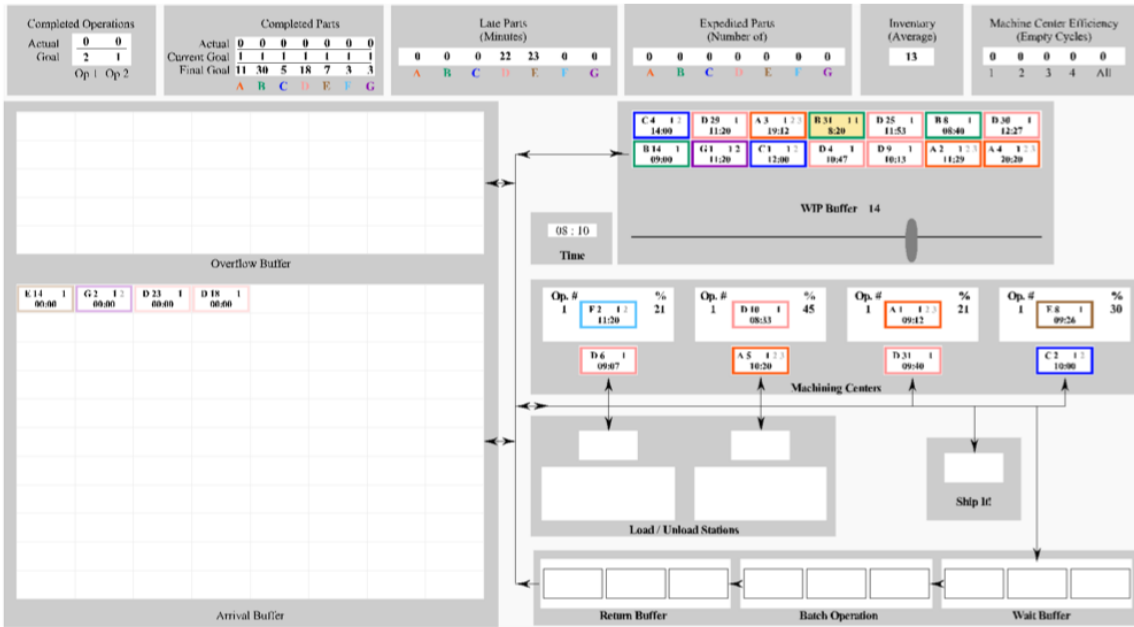
1.7 Alpha-Numeric Interface

A second interface, referred to as the *Alpha-Numeric* display, was created for the FMS system. The primary difference between the Alpha-Numeric and the Ecological interface involved substituting graphical representations for alpha-numeric representations. For example, although the production overview display was removed (see Figure 1.5), functionally equivalent information was still provided in the alpha-numeric representation. The Completed Parts infographic (upper left panel in Figure 1.5) provides alpha-numeric representations for each part type, including goal production requirements to meet daily shift demands (Final Goal), adjusted goals relative to the current time in the 10-hour shift (Current Goal), and current production levels (Actual) of the agent.

The analogical representation (left to right color infill) previously used to denote operation completion rate for individual parts within the Ecological interface was presented as a percentage value. Similarly, information regarding the three machining operations necessary for part completion in the ecological display (hatching) was replaced with a numerical value (i.e., OP1, OP2, OP3) in the Alpha-Numeric interface. Control inputs were executed in the same manner.

Figure 1.5

STE Not Utilizing CSE/EID Principles



1.8 Evaluation

A study was conducted to evaluate these two interfaces (Jackson, 2020). It was hypothesized that the Ecological interface would significantly improve performance relative to the Alpha-Numeric interface. The results of the experiment provide only modest evidence that participants were able to maintain control within the FMS more effectively through the Ecological interface than through the Alpha-Numeric interface. Agents were able to enter the target band (see Results section, for a description of tracking) and stay within the band significantly earlier with the Ecological interface as compared to the Alpha-Numeric interface. Agents were also more accurate in tracking production goals throughout the shift (measured by root mean squared error, constant position error, and modulus mean error). However, significant differences between interfaces were not obtained for a majority of the dependent variables. The only significant effect found in favor of the Ecological interface was obtained for the dependent variable of expedited parts. In addition, there were a few significant performance advantages that favored the Alpha-Numeric interface.

Several factors may have contributed to Jackson's (2020) lack of significance in performance measures between interfaces. Firstly, the two interfaces were perhaps not all that different regarding their information presentation to produce significant differences in performance. In terms of the three major principles of interface design (see Introduction), the interfaces were identical in the quality of support provided through direct manipulation, and only minor variations existed for visual momentum. For example, part type color-coding and general spatial layout were identical between interfaces.

Differences in direct perception certainly did exist. However, it is possible the design of the two interfaces did not produce decidedly different levels of support. While the production overview display was present in only the Ecological interface, functionally equivalent information was present in both interfaces (i.e., the Current Parts display). It is possible agents could have developed a single control strategy using this common display (e.g., ordering parts in the WIP based on alpha-numeric representations of due dates), as opposed to developing different strategies (e.g., developing a specialized strategy that leveraged the graphical information in the Production Balance display). To the extent that this happened, performance would have been equal across interfaces.

A second factor is the possibility that there were meaningful differences between the two interfaces. However, the task demands produced by our STE did not allow for those differences to be readily apparent. Ultimately, the task became repetitious and, therefore, too predictable. Both interfaces received identical quantities for each part type (i.e., A-G) in all 20 experimental sessions: no changes in overall production goals were introduced, nor were there any abnormalities or system disturbances. As a result, participants were not required to invent new strategies based on dynamically changing circumstances. Had the simulation incorporated more dynamic challenges, then more substantial performance differences might have been obtained.

These two possibilities are explored in the present study. Four alternative interfaces were designed to systematically vary the level of support provided by interface resources designed to incorporate (or not incorporate) the principles of direct manipulation (DM) and direct perception (DP): 1) DM present and DP present, 2) DM absent and DP absent, 3) DM present and DP absent, and 4) DM absent and DP present (see the method section for additional details). Several modifications to the STE were also introduced. First, a change was made to randomize the appearance of parts entering the arrival buffer throughout the simulated shift. Second, production goals were systematically varied by adjusting the required part types to meet daily demands for each of the 32 simulated shifts. Third, time pressure was applied by manipulating these production goals to require systematically larger portions of the available time within the simulated shift as the experiment progressed. Fourth, an element of irregularity was created by systematically introducing critical parts at later times in the simulated shift as the experiment progressed.

1.9 Predictions

We expected that the redesigned interfaces in this experiment would provide a broader range in the quality of decision-making and problem-solving support. We also expect that the less predictable and more challenging manufacturing constraints would serve to make these differences more readily apparent. Therefore, we predict that both direct perception and direct manipulation will significantly improve performance; we are interested in determining how they do so in an additive fashion (i.e., each in their own right) or in a more interactive manner (synergistic performance gains). In contrast, neglecting to apply direct perception and direct manipulation principles to the interface will significantly degrade performance. Applying either principle (direct perception or direct manipulation) in isolation should produce similar performance levels but intermediate to the Direct Perception/Direct Manipulation and No Direct Perception/No Direct Manipulation interfaces.

METHODS

2.1 Participants

Six (four male, two female) of eight Wright State University graduate students who participated in the Jackson (2020) experiment also participated in the present experiment. Participants were compensated $200 for their participation. All participants had normal or corrected normal visual acuity and color perception.

2.2 Apparatus

The experiment was conducted using an Apple Mac Pro (Model A1186, 2.8 GHz quad-core Intel Xeon, 8 GB memory, NVIDIA GeForce 8800 graphics card), Apple Cinema HD Display (Model A1083, 30", 2560 by 1600 resolution, 60 Hz refresh rate) and standard keyboard and mouse. Experimental sessions were conducted in a darkened and enclosed room. Director 11.5 (Adobe Systems, Inc.) software was used in programming and conducting the experimental events.

2.3 Synthetic Task Environment

A simulated FMS based on a real-world system for the production of engine parts (Dunkler, Mitchell, Govindaraj, & Ammons, 1988) was used. There were seven types of parts, labeled A through G. Each part type requires specific machining operations for completion. Parts B, D, and E required only operation 1. Parts C, F, and G required operation 1 followed by operation 2. Part A required operation 1, followed by a batch heat treatment, followed by operation 2, followed by a second batch heat treatment, and finally followed by operation 3.

There were four machining centers, each of which could perform all three machining operations. Each center held two parts: one that was being worked on and one that was being held in the machining center buffer. There were three system buffers capable of holding parts: 1) an arrival buffer (holding parts which can be pulled into the machining cell), 2) a work in progress (WIP) buffer (holding parts that are being worked on), and 3) an overflow buffer (holding parts in temporary storage). The arrival and overflow buffers had capacities of 88 and 40 parts, respectively. The WIP buffer had a variable capacity ranging from 0 to 21 parts. Two load/unload stations were used to position parts on a fixture prior to each machining operation (each station also had a buffer to hold a part). There was also a batch operation process which contained a wait buffer (parts accumulate here in lots of 3), an operation (application of heat treatment), and return buffer. Parts were moved in between all of these system components via a transportation system.

Simple automation was incorporated into the system using a first come, first serve (FCFS) control strategy which worked in the following fashion. Parts could be pulled into the manufacturing cell after they appear (automatically, one part per every fourth simulation update) in the arrival buffer. If there was an open slot in the WIP and there was at least one part in the arrival buffer, then the first available part was automatically brought into the WIP. Each part was automatically positioned using the load/unload station after entering the cell and before each machining operation. A part in the WIP was automatically routed to a machining center (or its buffer) if the next operation it needed matched the current operation of a machining center. A part was automatically returned from the machining center to the WIP after an operation had been completed (when additional operations were required) or out of the system (if all required operations had been completed). If a part was sent automatically to the WIP, and there were no open slots available, the part was rerouted to the overflow buffer. If the overflow buffer had parts and the WIP was below capacity, parts were routed from the overflow buffer to the WIP (automatic reroutes took place every fourth simulation update and took priority over pulling new parts into the WIP from the arrival buffer). A part was automatically placed in the last available slot in a buffer if it had multiple available slots. A part's icon was automatically updated to "potentially tardy" status by applying a yellow fill to its icon 20 system updates prior to its due date. A part was automatically labeled as "tardy" by the application of a red fill after its due date had expired.

A 10-hour work shift was simulated by equating one minute in the simulated shift to one update of the simulation (i.e., there were 600 simulation updates in a shift). The software was set for each simulation update to take 1.4 seconds to complete (and therefore approximately 14 minutes in real-time to complete a shift). However, the actual time to complete a shift was somewhat longer due to required overhead functions (e.g., data recording, user responses) and pausing the simulation during the execution of command input. Data were recorded at each simulation update or when critical events occurred.

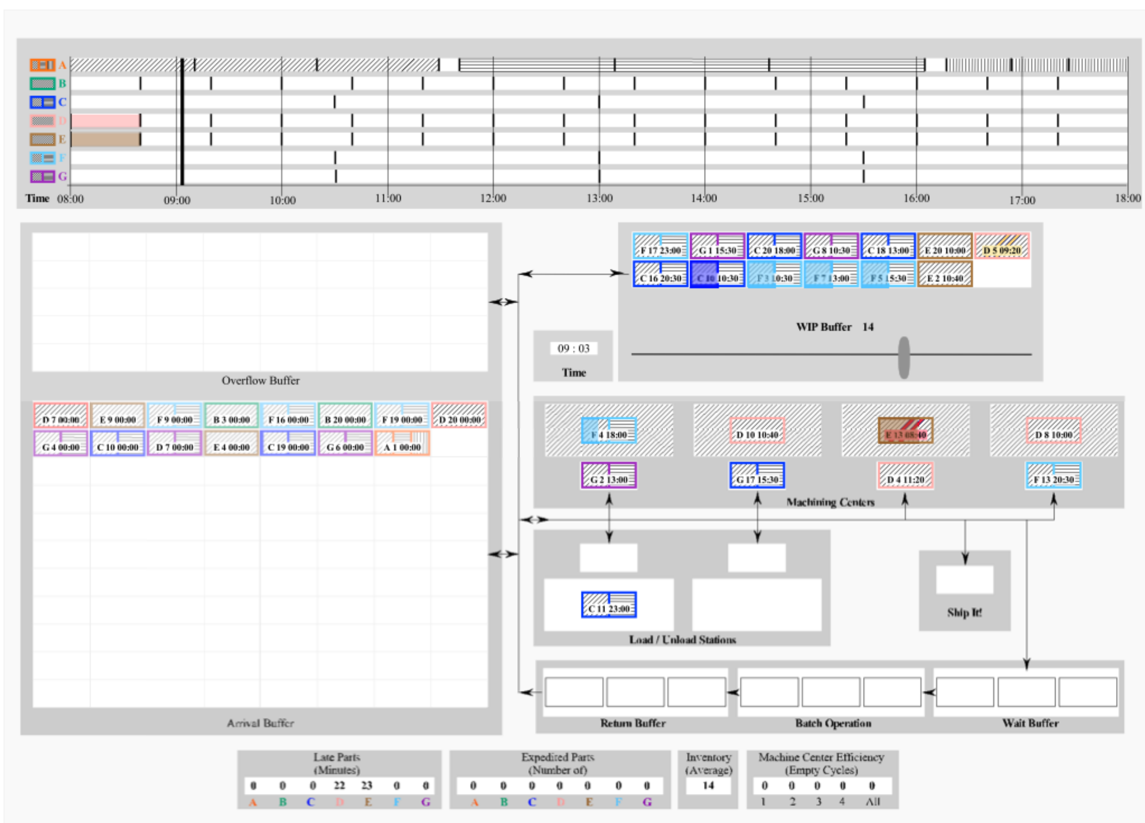
2.4 Interfaces

2.4.1 Direct Perception/Direct Manipulation (DP/DM) Interface

The DP/DM interface remained similar to the Jackson (2020) experiment (see detailed description in the Introduction section), with a few minor exceptions. The *Completed Operations* display and the *Completed Parts* infographics were removed from the Feedback Panel. The Feedback Panel was moved from the middle of the screen to the bottom of the screen (compare Figures 1.4 and 2.1). All other characteristics/features of the two interfaces were identical.

Figure 2.1

DP/DM Interface for FMS STE



2.4.2 No Direct Perception/No Direct Manipulation (NoDP/NoDM) Interface

The NoDP/NoDM interface is illustrated in Figure 2.2. This interface was similar in visible appearance to the Alpha-Numeric interface of Jackson (2020), with the following exceptions. The WIP Buffer and the Machining Center displays were always visible, but only one of the remaining five displays (Arrival Buffer, Overflow Buffer, Batch Operation, Load/Unload, and Stats / Goals) could be visible at the same time (in the single display slot at the bottom of the screen). Furthermore, the Completed Operations display was removed from the Stats / Goals section and the *Current Goal* information was removed from the Completed Parts display (compare Figures 1.5 and 2.2).

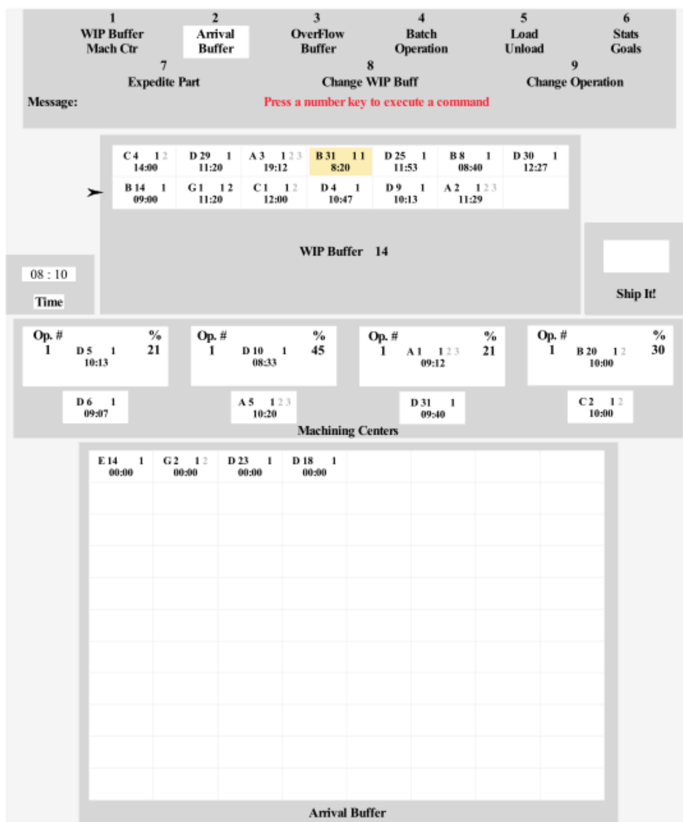
Control input was executed using the keyboard. The participant changed which display occupied the single display slot by pressing a number on the keyboard (see the display labels and numbers in the top panel of Figure 2.2). The participant pressed the number 9 key to initiate a change in the WIP size. The up and down arrow keys were used to increase or decrease the desired capacity, followed by a press of the return key to execute the command.

The participant initiated a change in machining operation by pressing the number 8 key. A transparent, light grey rectangle then appeared over the left-most machining center. The left and right arrow keys were used to position this rectangle over the desired machining center. The 0 key was then pressed to cycle through the three possible machining operations. Finally, the return key was pressed to execute the command.

A part was expedited by performing the following actions: pressing the number 7 key to initiate the command, pressing a prespecified number to indicate which buffer held the part to be moved, utilizing the arrow keys to position a small grey rectangle over the desired part, pressing the number 0 key to select a part, pressing a prespecified number to select the desired location, arrow keys to move the part to the desired slot in the new location, and finally pressing the return key to execute the command. Context-sensitive instructions were provided in the message area located in the top panel of Figure 2.2 for all commands.

Figure 2.2

No DP/No DM Interface for FMS STE

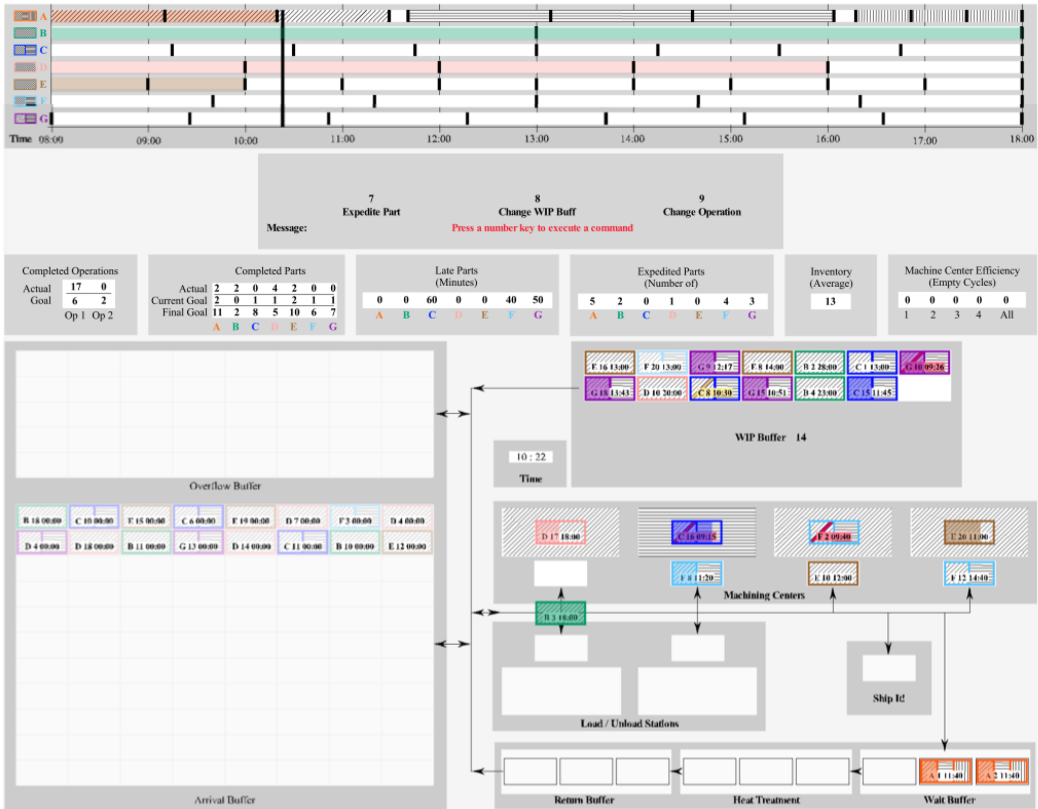


2.4.3 Direct Perception/No Direct Manipulation Interface

The DP/No DM interface (Figure 2.3) retained all visual aspects of the DP/DM interface, but control input was executed using the keyboard conventions described in the previous section (i.e., direct manipulation capabilities removed).

Figure 2.3

DP/No DM Interface for FMS STE

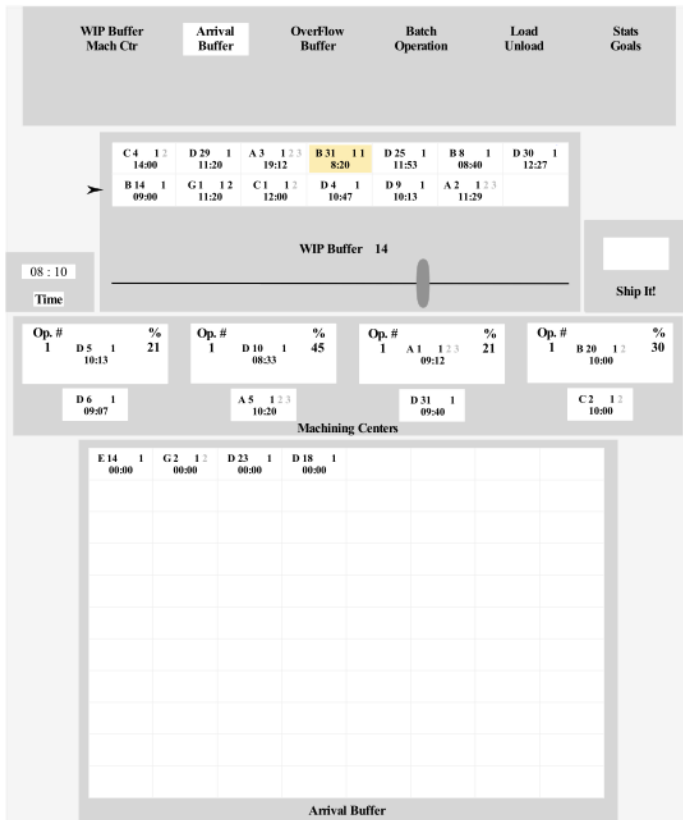


2.4.4 No Direct Perception/Direct Manipulation Interface

The No DP/DM interface (see Figure 2.4) retained the visual appearance of the No DP/No DM interface (see Figure 2.2), but control input was executed through direct manipulation. The change WIP size and the change machining operation commands were executed similarly to the DP/DM interface. A change in the display configuration was executed by rolling the mouse over a display label at the top of the interface (e.g., positioning the mouse over the OverFlow Buffer label made the display appear at the bottom of the screen). A part was expedited using direct manipulation. In the events that the destination buffer was not visible in the interface, the participant could point, click, and drag the part to be expedited over the appropriate buffer label at the top of the screen (causing the destination display to become visible), and then execute the command by continuing to drag and drop the part into the desired location.

Figure 2.4

No DP/DM Interface for FMS STE



2.5 Procedure

Informed consent was obtained. Participants were informed to prioritize their performance in the following manner during the initial sessions: 1) complete the exact number of parts for each part type to meet daily production goals, 2) limit the number of tardy parts, 3) minimize the inventory levels used in a simulated 10-hour shift, 4) maximize the machining center efficiency, and 5) minimize the total number of operations that were performed during the shift.

Participants completed eight experimental sessions (approximately 1 and 1/2 hours each, once per day). In the first two sessions, an experimenter sat in the experimental room and was available to answer questions regarding the interfaces (but not regarding any strategies). Participants completed one simulated shift using each of the four interfaces in a session. The order of interface appearance across sessions for each participant was controlled via a Latin squares counterbalancing technique. In the first four experimental sessions, a participant experienced each interface exactly once as the first, the second, the third, and the fourth interface in an experimental session. This occurred again in the second set of four experimental sessions, except that the specific orders were different (note that the specific orders were also different between participants).

Thirty-two shifts were developed. A pool of parts for use in each shift was formed by combining 6 part A's and 20 of each of the other part types (i.e., a total of 126 parts). The production goals for each part type were varied between shifts, as illustrated in Table 2.1. These production goals were crafted to systematically decrease the difference between the total amount of available machine processing time in a shift (40 hrs: 10 hrs each for four machines) and the amount of processing time required to complete parts, thereby increasing the difficulty of achieving production goals as the experiment progressed. The maximum excess processing time (4 hours total) occurred in an early shift; the minimum excess processing time (5 min) occurred in a late shift.

Table 2.1

Daily Production Goals for Part Types Across Sessions

Part Type	Scenario																															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
A	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
B	3	16	2	3	19	14	14	5	9	14	3	4	19	15	10	5	2	2	6	20	10	6	10	6	10	7	2	2	2	5	3	2
C	7	6	5	6	8	4	7	2	6	4	6	5	3	4	7	10	9	8	7	2	3	5	11	7	10	6	10	6	9	7	6	10
D	15	9	14	18	3	2	12	7	11	6	11	17	19	15	8	10	2	5	6	5	20	8	8	7	3	4	10	7	5	2	12	3
E	6	13	19	6	6	11	6	9	12	9	8	6	19	15	12	4	2	10	6	10	5	4	6	7	2	6	13	6	9	3	4	4
F	8	9	5	3	7	7	4	8	3	9	8	6	3	4	8	6	10	6	7	2	5	12	4	7	10	8	3	6	7	9	8	8
G	5	1	4	8	5	6	6	8	7	4	6	8	3	4	4	7	8	7	7	10	8	6	8	7	8	10	8	10	8	10	7	9

Order of appearance was initially determined randomly without replacement for the 126 parts. The 22 parts at the top of the order were used to initialize the simulation: they were assigned to the 14 slots in the WIP and the eight slots in the machining centers. The remaining 104 parts were then assigned to appear in the Arrival Buffer at one of the 600 simulation updates. The due date of "00:00" was assigned to a part when it became visible in the arrival buffer. When a part was pulled into the manufacturing cell from the arrival buffer it was assigned the next available due date for that particular part type.

The appearance of a sufficient number of multiple-operation parts to meet production goals was systematically delayed across scenarios to increase task difficulty further. The earliest average time for the required number of multi-operation parts to appear in the arrival buffer ranged from 130 min (shift 1) to 340 min (shift 32) in approximately 10 to 15 min increments. This modification was achieved by swapping the appearance time of a multiple-operation part (i.e., one that appeared too early for the average time required for that particular shift) with the appearance time of a single operation part that occurred later (i.e., in the desired time frame for the multiple parts of that shift).

The experimenter entered the correct experimental settings for interface and shift; the participant started the simulation by clicking on a start button. The participant controlled the simulation via the controls present in each interface. The participant could 1) override the automation and expedite the scheduled processing of a part, 2) change machining center operations, and 3) alter the capacity of the WIP (ranging from 0 to 21). Response time for the three basic control inputs was measured (1/20th sec accuracy) from the time that the participant initiated the command until the participant completed the command. The simulation was paused from the initiation of a control input until the participant completed the command (and the associated updates to system state and changes in displayed information were completed). Participants were offered a short break between the scenarios in a session if they so desired.

RESULTS

The following procedure was used for the analysis of each dependent variable. Scores were first calculated for each part type or machining center in a session. Outliers were identified using the test described in Lovie (1986, pp. 55-56): $T_1 = \frac{(x_{(n)} - \bar{x})}{\sigma}$ (1) where $x_{(n)}$ is a particular observation (one of n observations), x is the mean of those observations, and σ is the standard deviation of those observations. The remaining scores were then averaged across part types (or machining centers) to obtain an overall score for each shift. Nonparametric tests were conducted to determine if the outlier distribution was random (none of these tests were significant). Outliers were not identified for the inventory variable (a single score was obtained for the shift). A 4 (interface, within-subject: DP/DM, DP/NoDM, NoDP/DM, NoDP/NoDM) × 8 (day) repeated-measures ANOVA was conducted for each of the 16 dependent variables.

Six contrasts were performed to compare paired performance differences between means (see the labels and contrast weights in Table 3.1) when a main effect of interface was present. Significant interaction effects were also analyzed by conducting trend analysis to assess differences in interface performance across days. Simple main effects of interface by day were investigated by repeating the six contrasts for each day (day 1-8). Two sets of dependent variables were used to assess differences in performance across interfaces. The first set of dependent variables are based on the premise that FMS STE cell scheduling and processing control objectives (while not inherently complimentary) mimic real-world constraints and goals for a flexible manufacturing system (see Procedure section). The second set of dependent variables is an adaptation of measure of control theory (primarily used in continuous-variable systems like process control; see Poulton, 1974) for use in our discrete variable system. The aggregate of all 16 dependent variables can be parsed in two distinct measures; the first describes fundamental aspects of basic control activity, the second describes the quality of performance within the work domain.

3.1 Measures Concerning Fundamental Aspects of Basic Control Activity

3.1.1 Expedited Parts

The *Expedited Parts (Control)* dependent variable is defined as any movement of a part type (A-G) by the operator to bypass the automated processing (both within and between buffers; i.e., Arrival, Overflow, WIP, and Machining Centers) during a shift. An expedited part score was calculated by totaling the number of times an operator moved a part within a shift.

The *Expedited Parts (Time)* dependent variable is a recording of the average amount of time elapsed (in seconds) during the expedition of a part by a supervisory agent. For direct manipulation interfaces (i.e., DP/DM, No DP/DM) the expedited parts (time) latency scores were measured from the selection (through mouse input) of the relevant part to the deselection of the same part to its new location. For non-direct manipulation interfaces (i.e., DP/No DM, No DP/No DM), the expedited parts (time) latency scores were measured from the initial input command (key bound) to the execution of the said command.

The main effect of interface was significant for Expedite Parts (control), $F(3, 15) = 17.81$, $p < 0.00004$ (see Figure 3.1.1), and Expedite Parts (Time) $F(3, 15) = 58.08$, $p < 0.000001$; as well as main effect of day for Expedite Parts (control) $F(7, 35) = 7.86$, $p < 0.00001$, and Expedite Parts (time) $F(7, 35) = 18.38$, $p < 0.001$. A two-way interaction between interface and day was significant for Expedite Parts (time) $F(21, 105) = 11.25$, $p < 0.000001$ (see Figure 3.1.2).

Figure 3.1.1

Mean Value for Quantity of Expedited Parts, Main Effect of Interface

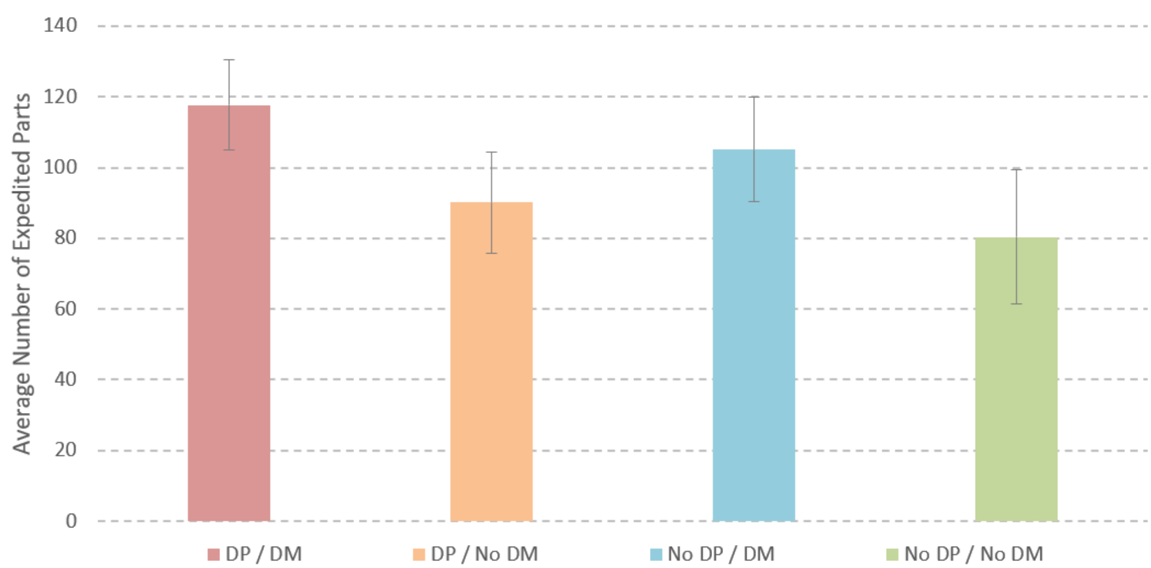
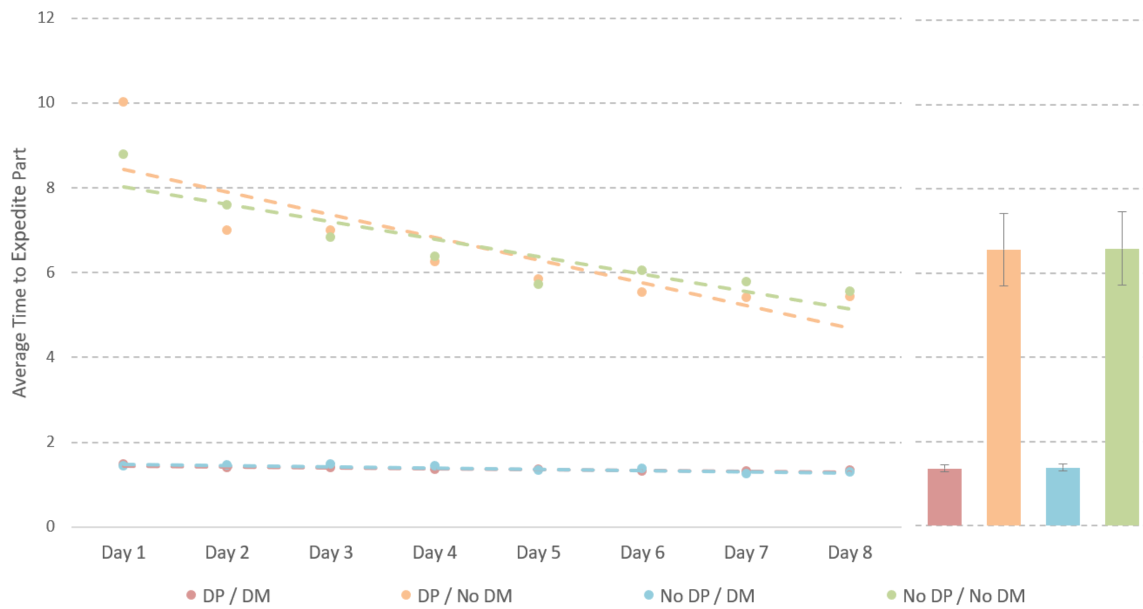


Figure 3.1.2

Mean Value for Latency of Expedited Parts, Interface by Day Interaction Effect



3.1.2 Work-In-Progress Buffer Capacity Adjustment

The *Change WIP Control* dependent variable calculations were made by totaling the number of adjustments made to the WIP buffer slider to alter buffer capacity (i.e., changes between the capacity of 0 to 21) within a shift.

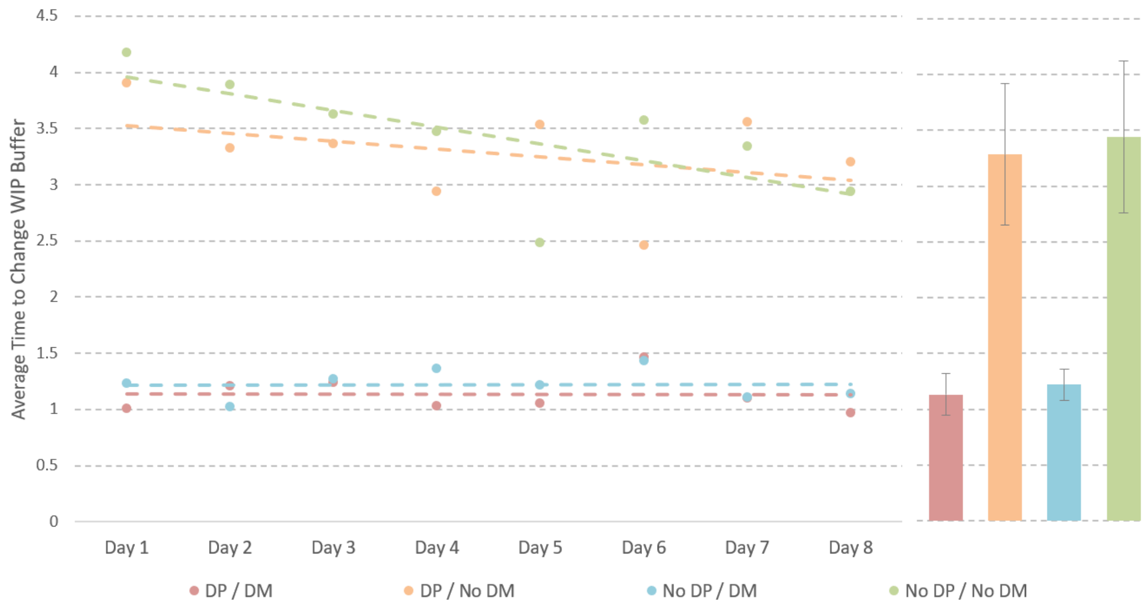
The *Change WIP (Time)* dependent variable is a recording of the average amount of time elapsed during the adjustments made to the WIP buffer slider to alter buffer capacity by a supervisory agent. For direct manipulation interfaces, the Change WIP (time) latency scores were measured from the selection (through mouse input) of the slider bar to the deselection of the slider bar. For non-direct manipulation interfaces, the Change WIP (time) latency scores were measured from the initial input command (key bound) to the execution of the said command.

The main effect of interface was significant for Change WIP (time), $F(3, 15) = 15.77$, $p < 0.00007$; as well as the main effect of day for Change WIP (control) $F(7, 35) =$

2.73, $p < 0.03$. A two-way interaction between interface and day was significant for Change WIP (time) $F(21, 105 = 1.69, p < 0.05$ (see Figure 3.2).

Figure 3.2

Mean Value for Latency of Change WIP, Interface by Day Interaction Effect



3.1.3 Machining Center Cell Operation Change

Scores for the dependent variable of machining center cell operation change (Change OP Control) were calculated by totaling the number of adjustments made to machining center cells (4) operations (i.e., change between operations 1-3) within a shift.

The *Change OP (Time)* dependent variable is a recording of the average amount of time elapsed during the adjustments made to the machining center cells (4) to alter their operational state by a supervisory agent. For direct manipulation interfaces, Change OP (time) latency scores were measured from the initial selection (through mouse input) of the operation cell to the final manipulation of the said cell. For non-direct manipulation interfaces, the Change WIP (time) latency scores were measured from the initial input command (key bound) to the execution of the said command.

The main effect of interface was significant for Change OP (control), $F(3, 15) = 5.49$, $p < 0.01$ (see Figure 3.3.1), and Change OP (time) $F(3, 15) = 150.62$, $p < 0.000001$; as well as the main effect of day for Change OP (time) $F(7, 35) = 8.52$, $p < 0.000005$. A two-way interaction between interface and day was significant for Change OP (time) $F(21, 105) = 4.02$, $p < 0.000001$ (see Figure 3.3.2).

Figure 3.3.1

Mean Value for Quantity of Change OP, Main Effect of Interface

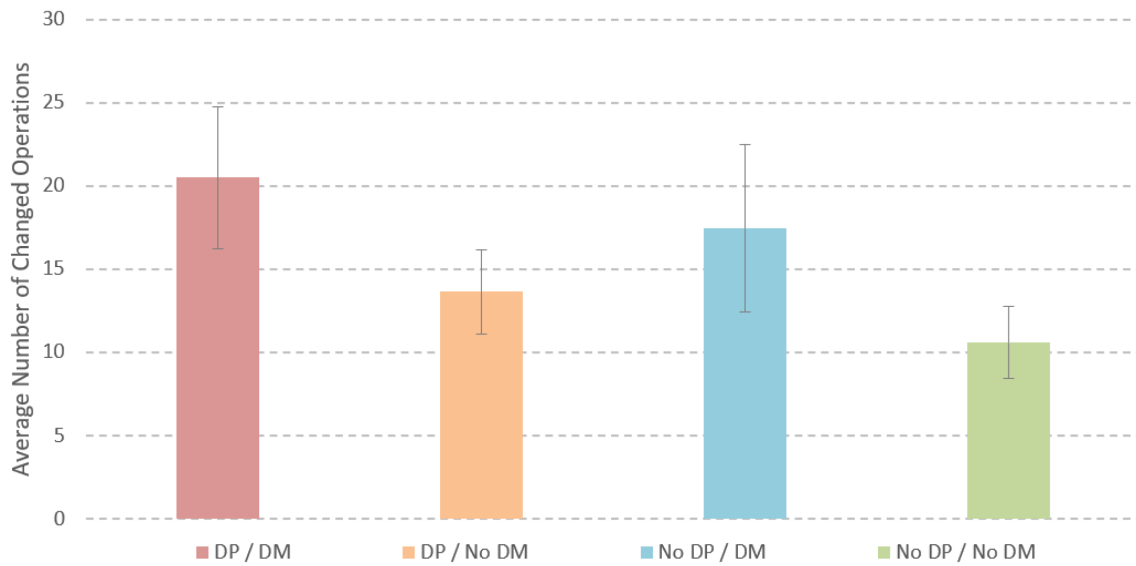
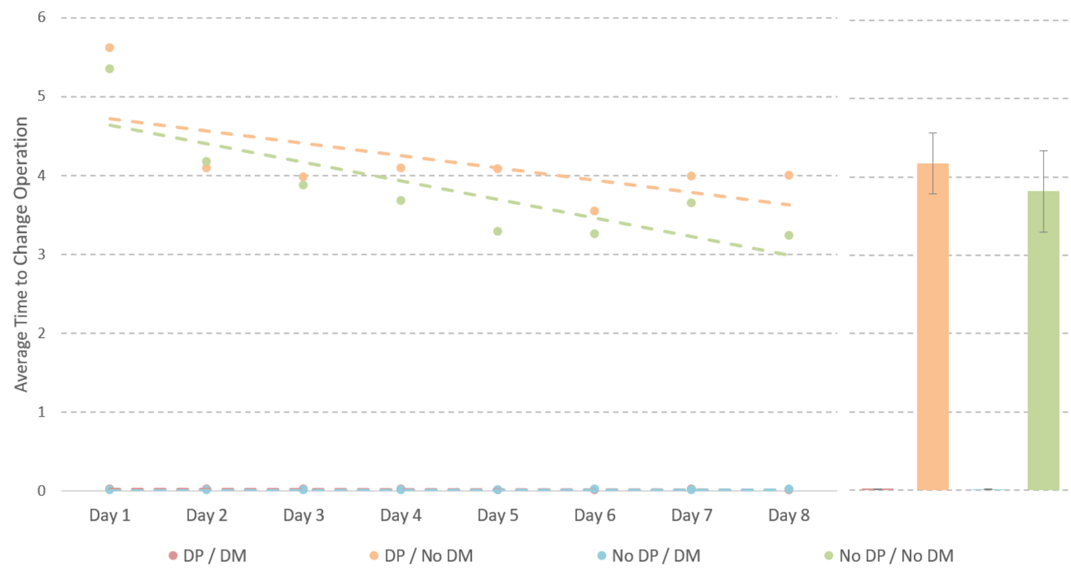


Figure 3.3.2

Mean Value for Latency of Change OP, Interface by Day Interaction Effect



All three significant Interface by Day interactions revealed a very similar pattern of performance. Participants produced uniformly low response latencies (see Figures 3.1.2, 3.2, and 3.3.2) flat across days when direct manipulation was present in the interface (DP/DM, No DP/DM). When direct manipulation was not present in the interface (DP/No DM, No DP/No DM) participants produced higher response latencies (represented through higher scores) to execute control input. Still, participant scores became better (witnessed through the negatively sloped linear trends) with the non-direct manipulation interfaces with additional experience. The linear trend analysis revealed that ten of 12 contrasts were significant, indicating that the slopes of these two sets of lines (i.e., those with and without direct manipulation) were significantly different (see Figure 3.4a).

Figure 3.4b lists both alpha-numeric and graphical representations of the contrasts conducted to test for the simple main effects of interface at Day 8. A significant difference between two interfaces is represented by an alpha-numeric representation of the F value and probability level. The visual appearance of the associated graphical icon denotes the presence or absence of direct perception (red, left square) or direct manipulation (right square, blue) and signifies which of the two interfaces being compared is the statistically superior performing interface. Figure 3.4b reveals that all twelve contrasts for the simple main effects of interface at Day 8 were significant. The patterns in the graphical icons (i.e., the presence of blue fill) reveals that the response latencies of the interfaces with direct manipulation applied remained significantly lower than those interfaces without direct manipulation at the end of the experiment.

Figure 3.4

Contrast Effects for Significant Interface by Day Interactions

Contrast Between Means

Direct Perception | No Direct Perception

Direct Manipulation | No Direct Manipulation

		DP/DM vs. DP/NoDM	DP/DM vs. NoDP/DM	DP/DM vs. NoDP/NoDM	DP/NoDM vs. NoDP/DM	DP/NoDM vs. NoDP/NoDM	NoDP/DM vs. NoDP/NoDM
		Contrast Number					
		1	2	3	4	5	6
Dependent Variable		**Outcome**					
Expedite Parts (Time) Trend	F (1, 5) =	34.70		19.10	37.04		16.46
	p <	0.003		0.008	0.002		0.01
Expedite Parts (Time) Day 8	F (1, 5) =	34.44		30.59	32.38		29.24
	p <	0.003		0.003	0.003		0.003
Change WIP (Time) Trend	F (1, 5) =			12.42			8.60
	p <			0.02			0.04
Change WIP (Time) Day 8	F (1, 5) =	8.34		8.49	6.64		6.80
	p <	0.04		0.04	0.05		0.05
Change OP (Time) Trend	F (1, 5) =	12.82		13.73	12.79		13.72
	p <	0.016		0.014	0.016		0.014
Change OP (Time) Day 8	F (1, 5) =	80.88		90.15	80.78	8.27	89.74
	p <	0.0003		0.0003	0.0003	0.04	0.0003
		(A) Measures Describing Fundamental Aspects of Basic Control Activity					
Part Production (Abs) Trend	F (1, 5) =			11.65		10.19	
	p <			0.02		0.03	
Part Production (Abs) Day 8	F (1, 5) =						
	p <						
		(B) Measures Describing Quality of Performance in Work Domain					

Note. Colored fill represents the presence (dark fill) or absence (light fill) of the statistically superior performing interface within the corresponding contrast. Empty cells are not significant.

3.2 Measures Describing Quality of Performance in Work Domain

3.2.1 Production Goals

Participants were expected to complete, but not exceed, the number of parts required to meet daily demand within the STE. Goal progress was tracked and presented to the user through the Completed Parts infographic (i.e., No DP/DM, No DP/No DM) or Production Overview Display (i.e., DP/DM, DP/No DM). Scores for the dependent variable of

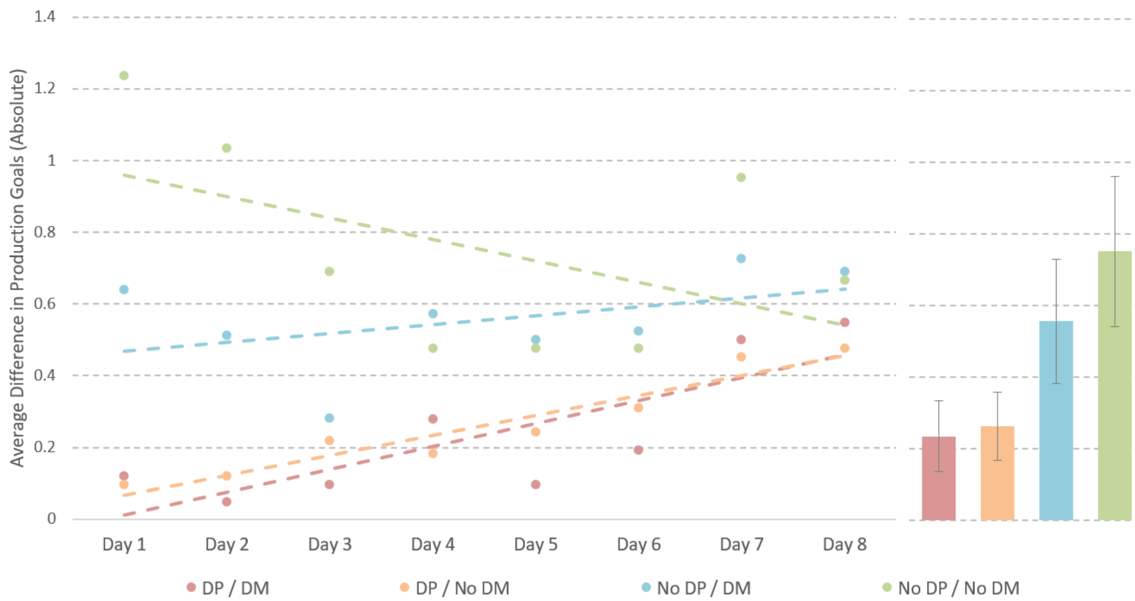
Signed Production Goals (comparing over-production, under-production biases across interface) were calculated by taking the goal value for a part type and subtracting the actual number of parts produced during a shift. Scores for the dependent variable of Absolute Production Goals (comparing meeting vs. not meeting discrete production goals across interface) were calculated by taking the absolute value of the difference between goal and actual part production for each part type.

The main effect of interface was significant for Production Goals (absolute), $F(3, 15) = 19.42$, $p < 0.00002$; as well as main effects of day for Production Goals (absolute) $F(7, 35) = 3.59$, $p < 0.006$. A significant two-way interaction between interface and day was significant for Production Goals (absolute) $F(21, 105) = 2.13$, $p < 0.007$ (see Figure 3.5). Contrast analysis of linear trends for Production Goals (absolute) can be seen in Figure 3.5.

For Production Goals (signed), only the main effect of day $F(7, 35) = 7.99$, $p < 0.000009$, was significant.

Figure 3.5

Mean Values for Production Goals (Absolute), Interface by Day Interaction Effect

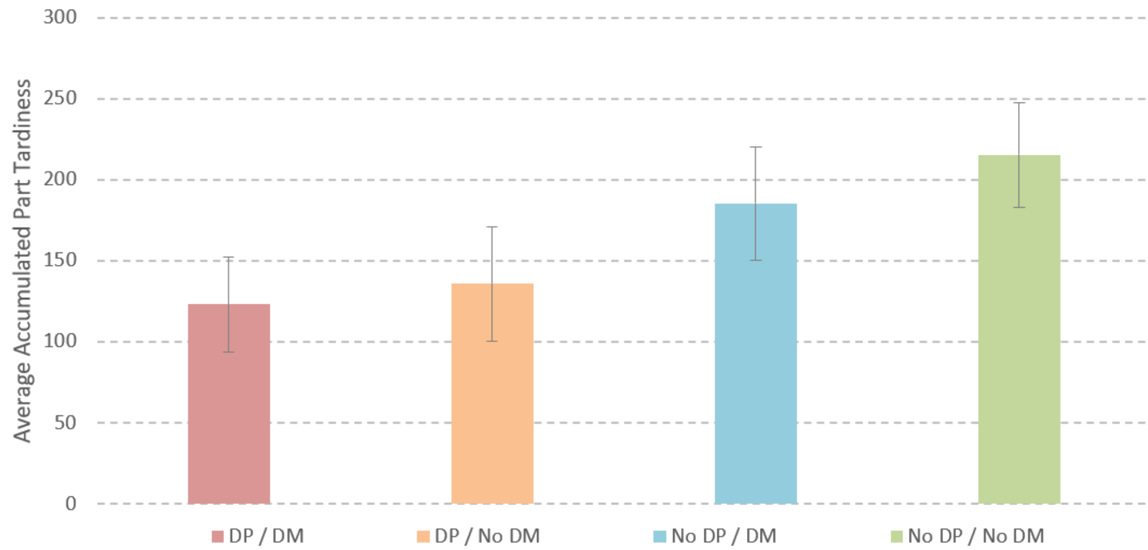


3.2.2 Part Tardiness

Participants were informed to limit the number of tardy parts within a shift. The *Part Tardiness (Minutes)* infographic displayed a 1-by-7 matrix (one column for each of the seven parts), each digit within the matrix would increase by one per scenario-minute (roughly 4 seconds real-time) that a corresponding part incomplete beyond the parts required completion time. Scores for the dependent variable of *Part Tardiness* were calculated by keeping a running total of tardy parts for each part type throughout a shift (i.e., incrementing the total for a part type by 1 for each part which was tardy at each of the 600 simulation updates).

The main effect of interface was significant for Part Tardiness, $F(3, 15) = 14.15$, $p < 0.0002$ (see Figure 3.6); as well as the main effect of day $F(7, 35) = 5.14$, $p < 0.0005$.

Figure 3.6
Mean Values for the Quantity of Accumulated Tardiness, Main Effect of Interface



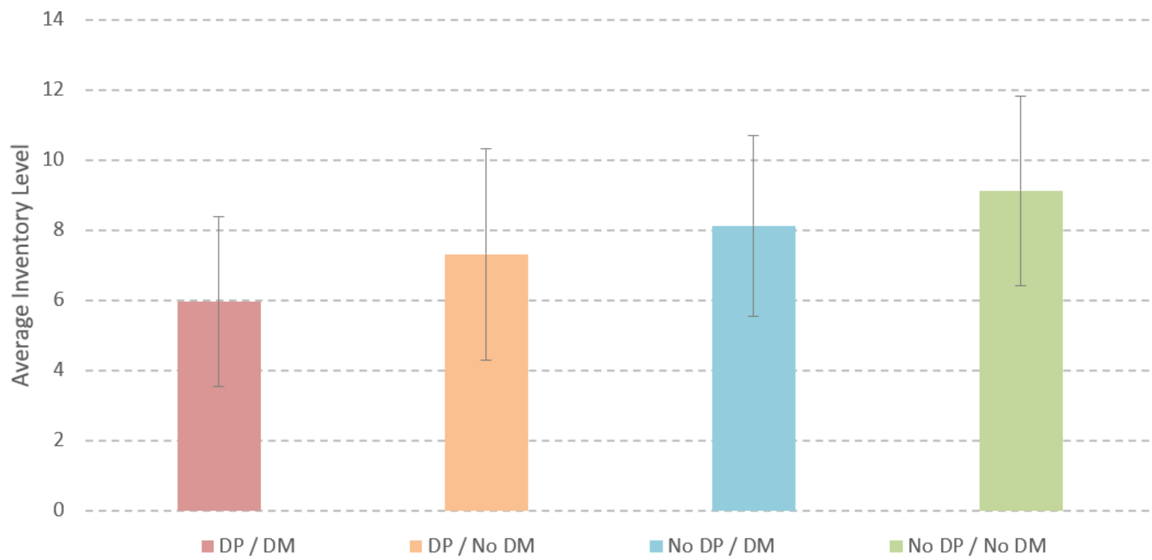
3.2.3 Inventory Level

Participants were instructed to minimize the total inventory levels within each session. Inventory is defined as all non-infinite temporary storage of parts within the FMS STE. Scores for the dependent variable of *Inventory Level* were obtained by summing the number of parts remaining in the manufacturing cell (i.e., machine buffers, load/unload stations, WIP, overflow buffer, and return buffer; arrival buffer excluded from FMS STE inventory).

Inventory Level was calculated as the total inventory sum/600 (where 600 is the total number of minutes per simulated shift, 10 hours). The *Inventory (Average)* infographic presented this value, updated in real-time to the supervisory agent. For inventory, the main effect of interface was significant $F(3, 15) = 6.53$, $p < 0.005$ (see Figure 3.7).

Figure 3.7

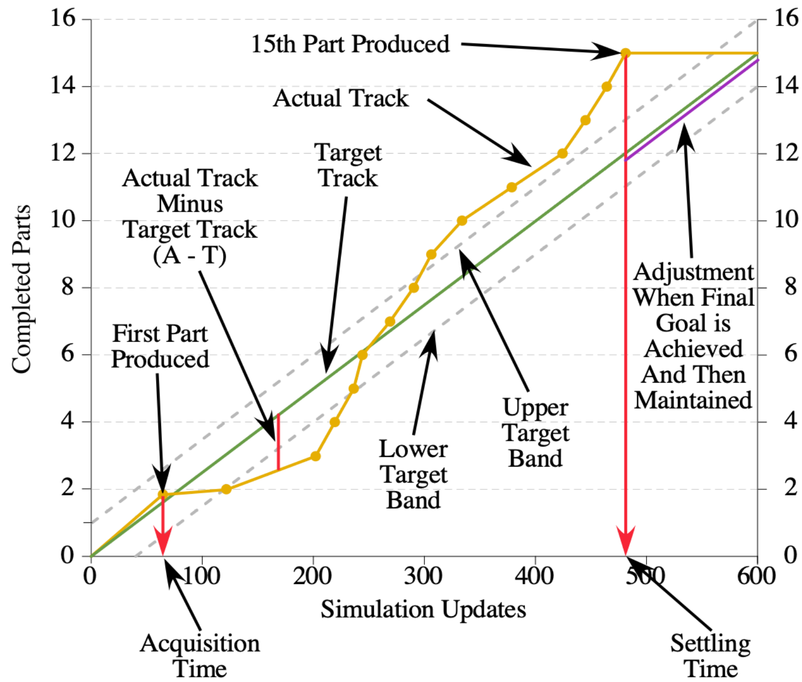
Mean Values for the Quantity of Inventory Level, Main Effect of Interface



Tracking. Performance techniques initially developed for manual control (i.e., tracking tasks) were adapted to track actual versus goal part production throughout the entire shift (Figure 3.8). The target track is represented as a straight line from the origin of a graph (x-axis coordinates are simulation updates, 0 – 600; y-axis coordinates are production goals) to a point on the y-axis corresponding to the goal for part production. A target band for performance with each part type is defined by adding one part to (i.e., the upper target band) and subtracting one part from (i.e., the lower target band) the target track at each point in the shift. The actual track (i.e., the participant's control performance for each part type in each shift) is generated by representing each completed part as a point in the graph (x value = shift time that part was completed; y value = the number of parts completed for that part type) and then adding line segments which connect each successive point.

Figure 3.8

Adaptation of Manual Control Measures to Discrete Process Manufacturing



3.2.4 Acquisition Time

The *Acquisition Time* dependent variable is calculated by determining the first simulation update (1-600) in which the actual track for a part type enters into the target band. If the actual track never manages to enter the target band, then a score of 600 is assigned.

3.2.5 Settling Time

The *Settling Time* dependent variable is calculated by determining the first simulation update the actual track enters the target band and then stays within the target band throughout the remainder of the shift. If the actual track does not wind up within the target band at the end of the shift, then a score of 600 is assigned.

An adjustment was made when settling time was less than 600 (i.e., when settling time occurred before the end of the shift): the segment of the actual track ranging from settling time to 600 was replaced by the corresponding segment of the target track. The rationale for this replacement is two-fold: 1) this constitutes perfect control performance (i.e., nothing can be done to improve control performance) and 2) it takes active control to keep it perfect (i.e., the automation will bring unwanted parts into the cell and then process them if control input is not applied). Any other scoring method either penalizes or conversely does not reward the participant for achieving and maintaining perfect goal production levels.

3.2.6 Quality of Control Error Estimates

Four estimates of the quality of control error (Poulton, 1974) were calculated using all 600 simulation updates in a shift. The formula for the *Root Mean Square (RMS) Error* dependent variable is $\sqrt{\frac{\sum(A-T)^2}{600}}$ (1), in which A is the y value of the actual track at a simulation update, and T is the y value of the target track at a simulation update. The formula for *Constant Position (CPE) Error* is $\frac{\sum(A-T)}{600}$ (2). The formula for *Modulus Mean (MME) Error* is $\frac{\sum abs(A-T)}{600}$ (3). The formula for *Standard Deviation of the Error (SDE)* is $\sqrt{\frac{\sum(A-\overline{CPE})^2}{600}}$ (4).

The main effects of interface and day were significant for the following dependent variables: Acquisition Time, $F(3, 15) = 16.66$, $p < 0.00005$ (inferface; Figure 3.9.1), $F(7, 35) = 5.76$, $p < 0.0001$ (day); Settling Time, $F(3, 15) = 25.02$, $p < 0.000004$ (inferface; Figure 3.9.2), $F(7, 35) = 5.25$, $p < 0.001$ (day); RMS Error, $F(3, 15) = 15.50$, p < 0.00008 (inferface; Figure 3.9.3a), $F(7, 35) = 9.33$, p < 0.000002 (day); Constant Position Error,

$F(3, 15) = 6.35$, $p < 0.006$ (inferface; Figure 3.9.3b), $F(7, 35) = 21.69$, $p < 0.000001$ (day); and Modulus Mean Error, $F(3, 15) = 16.66$, $p < 0.00005$ (inferface; Figure 3.9.3c), $F(7, 35) = 5.57$, $p < 0.0003$ (day). For Standard Deviation of the Error, only day $F(7, 35) = 121.99$, $p < 0.000001$ was significant. No significant interactions were present.

Figure 3.9.1
Mean Values for Acquisition Time, Main Effect of Interface

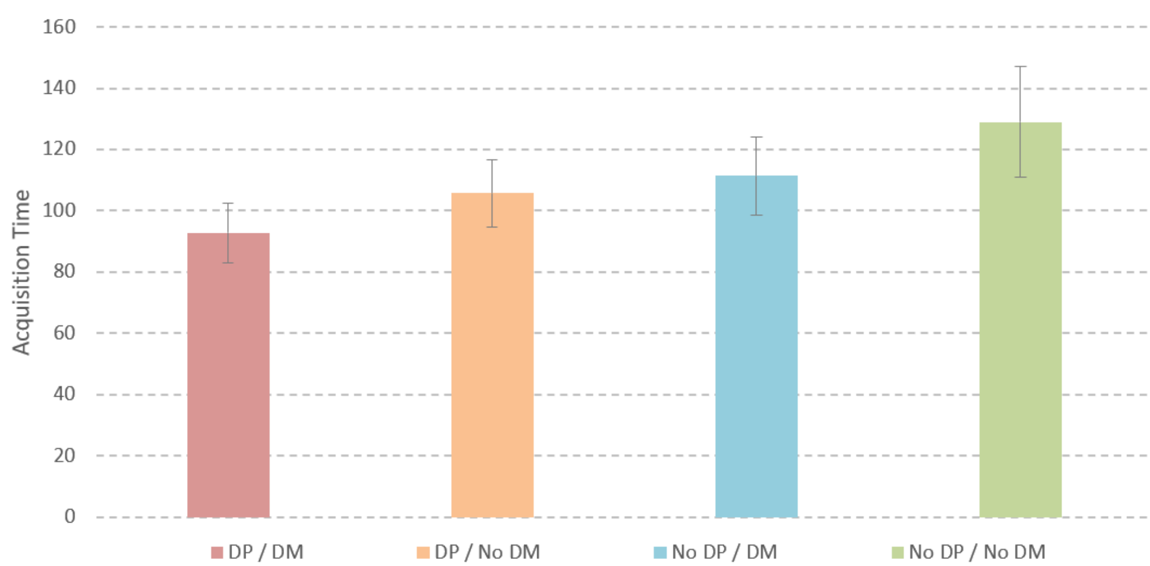


Figure 3.9.2

Mean Values for Settling Time, Main Effect of Interface

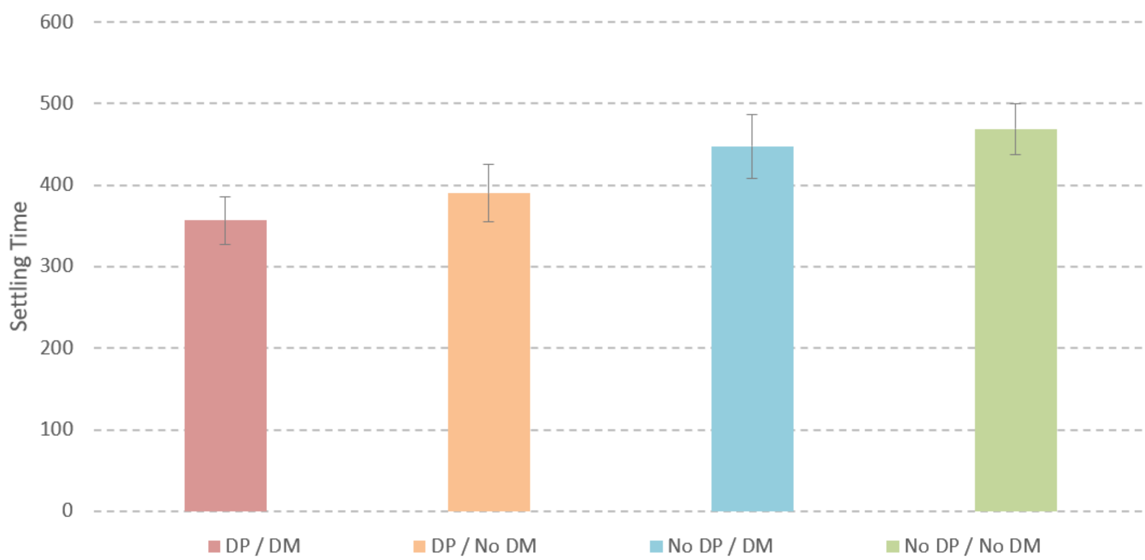
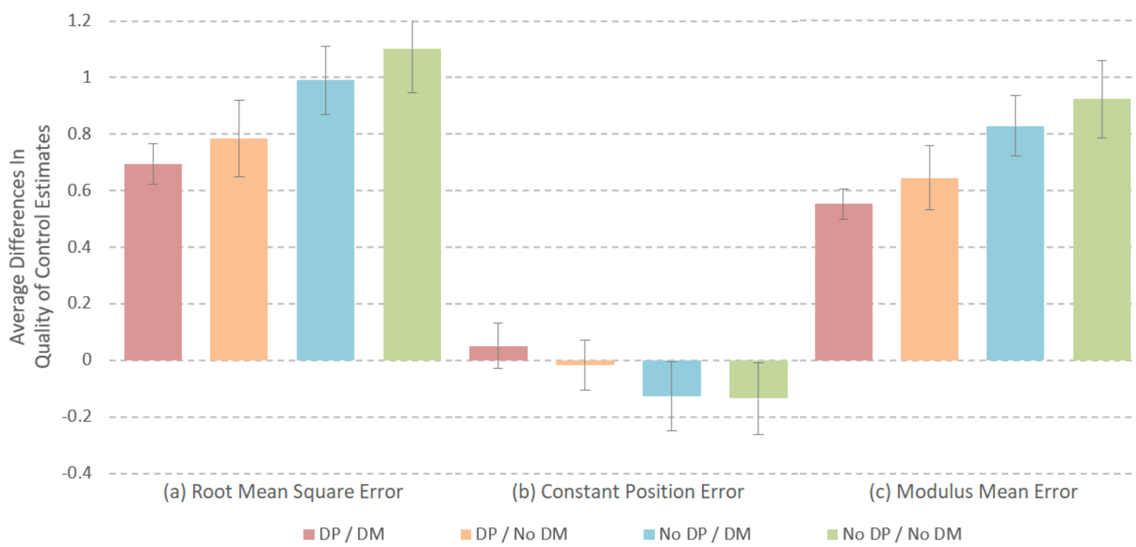


Figure 3.9.3

Mean Values for Significant Quality of Control Error Estimates, Main Effect of Interface



The pattern of outcomes obtained for work domain performance metrics indicates that the presence or absence of direct perception is the predominant factor controlling performance. For all of the dependent variables in which significant differences were found for interface, main effect of interface contrasts found interfaces which had the principle of direct perception applied resulted in significantly superior performance. The associated contrasts detailing differences between interface means are summarized in Table 3.1. Empty cells in Table 3.1 represent contrasts either not conducted (e.g., Part Production [Signed]) or that the contrasts were not significant (e.g., Inventory, Contrast 1).

Table 3.1

Contrast Table for Significant Main Effects of Interface

		Contrast Between Means					
		DP/DM vs. DP/NoDM	DP/DM vs. NoDP/DM	DP/DM vs. NoDP/NoDM	DP/NoDM vs. NoDP/DM	DP/NoDM vs. NoDP/NoDM	NoDP/DM vs. NoDP/NoDM
		Contrast Number					
		1	2	3	4	5	6
Interface		**Contrast Weights**					
DP/DM		1	1	1	0	0	0
DP/NoDM		-1	0	0	1	1	0
NoDP/DM		0	-1	0	-1	0	1
NoDP/NoDM		0	0	-1	0	-1	-1
Dependent Variable		**Outcome**					
Expediate Parts (Time)	F (1, 5) =	80.46		48.29	77.54		47.22
	p <	0.0003		0.001	0.0004		0.001
Expedite Parts (Control)	F (1, 5) =	27.62		22.80	9.36		22.88
	p <	0.004		0.005	0.03		0.005
Change WIP (Time)	F (1, 5) =	19.22		16.81	15.15		13.53
	p <	0.008		0.01	0.02		0.02
Change WIP (Control)							
Change OP (Time)	F (1, 5) =	284.22		107.11	282.64		106.75
	p <	0.00002		0.0002	0.00002		0.0002
Change OP (Control)	F (1, 5) =	6.67		22.31		19.90	
	p <	0.05		0.006		0.007	
		(A) Measures Describing Fundamental Aspects of Basic Control Activity					
Part Production (Signed)							
Part Production (Absolute)	F (1, 5) =		19.70	40.41	8.24	24.56	9.56
	p <		0.007	0.002	0.04	0.005	0.03
Late Parts	F (1, 5) =		14.21	35.68	15.17	13.57	
	p <		0.02	0.002	0.02	0.02	
Inventory	F (1, 5) =		15.83	86.21			
	p <		0.02	0.0003			
Acquisition Time	F (1, 5) =		9.73	112.15		20.33	6.93
	p <		0.03	0.0002		0.007	0.05
Settling Time	F (1, 5) =	6.99	17.93	49.09	15.80	85.78	
	p <	0.05	0.006	0.001	0.02	0.0003	
RMS Error	F (1, 5) =		22.1	22.44	27.94	15.25	
	p <		0.006	0.006	0.004	0.02	
Constant Position Error	F (1, 5) =		8.59	24.43		10.28	
	p <		0.04	0.005		0.03	
Modulus Mean Error	F (1, 5) =		28.05	25.97	25.85	15.09	
	p <		0.004	0.004	0.004	0.02	
Std. Deviation of the Error							
		(B) Measures Describing Quality of Performance in Work Domain					

DISCUSSION

4.1 Summary of Results

This experiment aimed to utilize a flexible manufacturing systems synthetic task environment to probe the potential effects of direct perception and direct manipulation principles in display design. In contrast to Jackson (2020), the combination of alternative interface designs and the modified task characteristics in this experiment successfully produced a more diverse set of performance outcomes. The results provide clear and consistent evidence that the design principles of both direct perception and direct manipulation were associated with significant improvements in performance in this simulated flexible manufacturing environment.

4.1.1 Patterns in Average Performance

The overall pattern of outcomes will be described in reference to Figure 4.1, which illustrates the results of the contrasts conducted to test the significant main effects of interface. The experimental results indicate apparent trade-offs between the representational format (i.e., direct perception), control input (i.e., direct manipulation), and the type of task to be performed (i.e., basic control input and work domain metrics).

Figure 4.1 presents the average performance for each interface (i.e., the main effect of interface) for all 16 dependent variables (standardized scores are illustrated, with better performance mapped into higher, positive standard scores). An examination of Figure 4.1 reveals several consistent patterns. Primarily, the pattern of results indicates the DP/DM interface was consistently the most effective, producing the greatest average performance for 14 of the 16 dependent variables (see red-filled bars in Figure 4.1). In contrast, the interface without direct perception and direct manipulation (No DP/No DM; see green-filled bars in Figure 4.1) was the least effective interface, producing the poorest performance for 15 of the 16 dependent variables.

The performance pattern for the remaining two interfaces (i.e., DP/No DM, No DP/DM) is dependent on the category of behavior being measured. The presence of direct manipulation (see blue-filled bars in Figure 4.1a) allowed participants to perform basic control inputs more effectively (across all six dependent variables). Conversely, the presence of direct perception (see orange-filled bars in Figure 4.1b) allowed participants to perform tasks defined by the work domain more effectively (in 9 of the 10 dependent variables).

Figure 4.2 presents a graphical representation of the contrast table for significant main effects of interface. The presence of a graphical icon represents a significant result (see Table 3.1 for corresponding statistical values); the visual appearance of an icon signifies which of the two interfaces being compared is associated with superior performance. Specifically, the presence of either a dark or light colored fill denotes the presence or absence of direct perception (red, left square) or direct manipulation (right square, blue) in the interface which produced significantly better performance.

Figure 4.1

Average Patterns of Main Effects of Interface for Dependent Variables

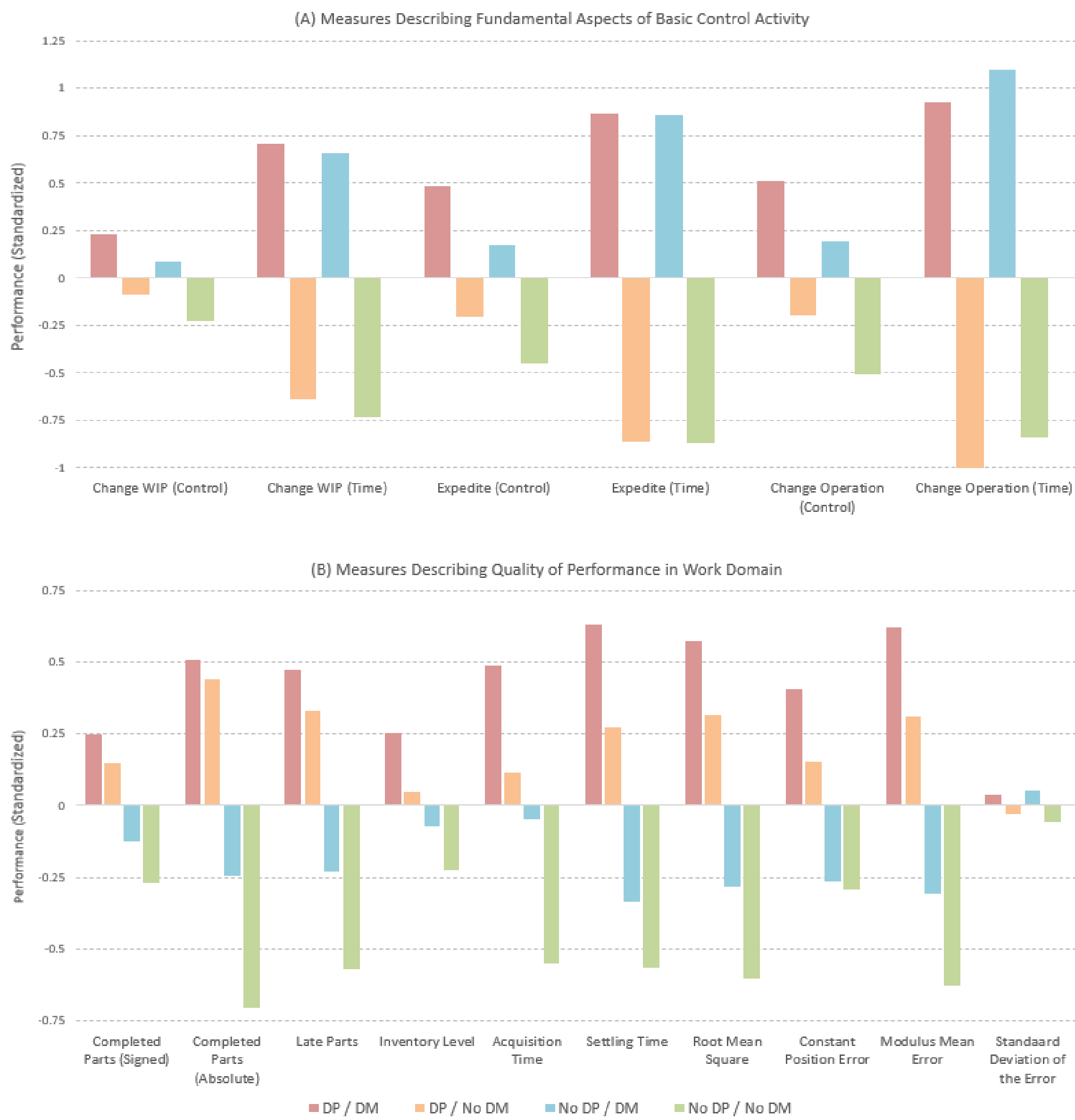
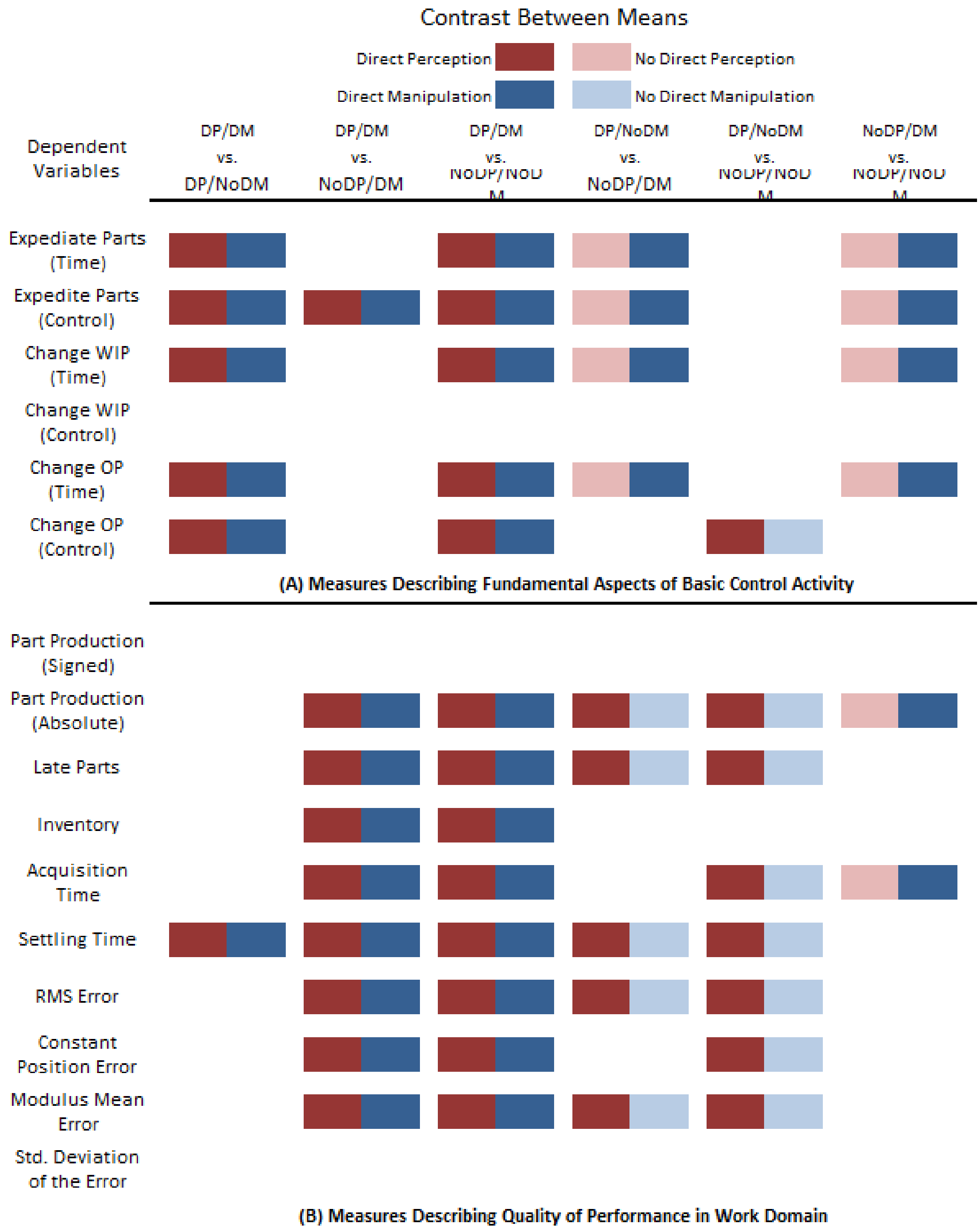


Figure 4.2

Graphical Representation of Contrast Table for Significant Main Effects of Interface



4.1.2 Basic Control Activity

The goal of applying direct manipulation in the interface is to transform the interaction utilized by the supervisory agent from one requiring limited-capacity cognitive resources (i.e., executive control input) to one which utilizes powerful perception-action resources. Results obtained from five of the six dependent variables (Figure 4.2a) for basic control input provide evidence that this was achieved successfully and that direct manipulation made it easier for controllers to execute control input.

Figure 4.2a (presenting a color-coded graphical representation of Table 3.1) reveals that direct manipulation (represented by dark blue fill on the right side of an icon) present in 18 of the 19 significant contrasts between interfaces (Contrast 1-6) for tasks defined by basic control activity (i.e., Change WIP, Change Machining Center Cell Operation, Expedite part; Figure 4.2b). More specifically, the outcome of the contrasts, which directly compared the presence or absence of direct manipulation (i.e., comparisons 1, 3, 4, and 6), revealed that in all significant comparisons, the interfaces with direct manipulation were always associated with greater performance. In contrast, only 1 of the 10 contrasts was significant when the absence (i.e., contrast 5) of direct manipulation was held constant between the two interfaces being compared.

4.1.3 Work Domain Performance Metrics

A decidedly different pattern of outcomes was obtained for the second category of dependent variables: work domain performance metrics (i.e., Part Production Signed, Part Production Absolute, Part Tardiness, Inventory, Acquisition Time, Settling Time, and Quality of Control Error Estimates). The findings obtained for these dependent variables indicate that the presence or absence of direct perception is the predominant factor moderating performance for work domain metrics. This is evident in the fact that direct perception (i.e., dark red fill, left side) was present in 29 of the 31 significant contrasts between interfaces (Contrast 1-6) for measures of work domain metrics. More specifically, the outcome of the contrasts which directly compared the presence or absence of direct perception (i.e., comparisons 2, 3, 4, and 5) revealed that 28 of the 32 comparisons were significant and that the interface with direct perception was always associated with significantly better performance. No significant main effects involving interface were obtained for the standard deviation of the error or the signed difference between goal production and actual production levels. In contrast, when direct perception was held constant (i.e., in contrasts 1 and 6), only 3 of the 16 contrasts were significant, and there was a mixed pattern of results.

4.1.4 Tracking Performance Metrics

We found that adapting manual control metrics as a means of tracking and measuring performance was very successful in offering greater insight into the participants' process of completing session objectives above and beyond that of outcome-based measures. Contrast 4 is particularly relevant as both direct perception and direct manipulation were simultaneously varied. There is a clear pattern that divides dependent variable specific performance between the presence or absence of either direct perception or direct manipulation.

Direct perception significantly decreased the time taken for part production levels to enter the target band of acceptable performance (acquisition time) and stay within that target (settling time) until the end of the simulated shift. For measures of tracking error (i.e., CPE, RMS, MME), 11 of the 12 contrasts between interfaces indicated improvements in the participants' ability to track production goals throughout the shift when direct perception was applied. Beyond this, there were also significantly fewer excess parts at the end of a shift (i.e., lower levels of inventory) and four significant contrasts suggesting participants were more effective in meeting scheduled production goals (absolute values).

However, the interface and day significant interaction effect for production goals (absolute) indicates that any performance facilitated through the application of direct perception disappeared by the final session (Day 8, see Figure 3.5). Remember, participants were instructed to prioritize production goals above all else. The results provide evidence to support our belief that participants were successful in following this instruction. However, doing so without the application of direct perception in the interface came with the trade-off of increased cognitive effort, evident by the significant decrements in performance that were obtained elsewhere for non-direct perception interfaces (see Figure 4.1)

4.2 Implications for Display Design

This study revealed several performance differences that were related to both the representational format (i.e., direct perception) and the control input (i.e., direct manipulation) that testify to the superiority of the DP/DM interface when compared to opposing interfaces that lacked either one or the combination of these principles of design.

Through the application of direct perception, participants performed significantly better, quantified by more accurate part production (absolute) counts for session goals, more timely completion times (decreased part tardiness), generally smaller inventory levels, and less pronounced acquisition time, settling time, and error rates (i.e., RMS, CPE, MME). Likewise, agents completed more actions on the system (expedite parts, change WIP, change op) and when direct manipulation was applied. Disparities in performance between interfaces were pronounced.

The results described present evidence that the presence of direct perception and direct manipulation (DP/DM) in interface design produced an additive effect allowing for greater support towards supervisory agents in their efforts to obtain information regarding the current system state more effectively than the interfaces with either only singular or neither principle applied. An interpretation requires considering the joint constraints on performance introduced by the evaluation goals and applied principles.

Complex socio-technical systems require a complicated display, incorporating a great deal of information about the underlying work domain (see Introduction) to portray all necessary information to the agent. Several aspects of the evaluation might indicate that the application of direct perception and direct manipulation (DP/DM) was easy to learn and use. These discoveries will be explored from a CSE/EID perspective, emphasizing the three interface design principles (i.e., direct perception, direct manipulation, and visual momentum) outlined in the Introduction section.

4.2.1 Direct Perception

The interface design goal of direct perception (DP/DM, DP/NoDM) was specifically designed to support agents by implementing several graphical representations (i.e., analogies and metaphors) that were uniquely adapted to the constraints of the flexible manufacturing system work domain. Content mappings (i.e., domain constraints to interface constraints) provided information from various categories of the abstraction hierarchy pertaining to the work domain (see *EID in Flexible Manufacturing)* constraints were present in the interface, as were summaries of STE resources and goal-relevant objectives. Format mappings (i.e., display constraints to agent constraints) presented as graphical representations (i.e., analogies and metaphors) were carefully designed to reflect the inherent constraints of the work domain information (e.g., machining center cell operation selection, part production operation requirements) and to support information pickup (e.g., graphical, categorical & analogical visual information corresponding to work domain constraints). Work domain constraints introduced through direct perception interfaces allowed for skill-based processing (i.e., immediate perception of work domain affordances and action upon those affordances). The direct perception allowed the agent to use powerful visual perceptual skills to obtain information regarding the agent's current completion rate of FMS STE objectives.

In contrast, the NoDP/DM and NoDP/NoDP interfaces did not support direct perception due to the content mappings having poor quality and little regard for the levels of abstraction (i.e., information). In addition, STE objectives were presented in a piece-meal fashion (e.g., no overview display), requiring participants to navigate through multiple displays to obtain information regarding various information regarding the system state. Format mappings were equally unsupportive. The primary form used to represent FMS STE resources was alphanumeric as opposed to analog and graphical. This difference forces the agent to use limited cognitive resources (i.e., working memory) to derive information mentally. As a result, acquiring information with the non-direct perception interface (NoDP/DM, NoDP/NoDP) required deliberate search (i.e., navigation through display panels to locate goal-relevant data) and extensive cognitive processing (to attend to and manipulate data for decision-making purposes).

4.2.2 Direct Manipulation

The goal of direct manipulation was achieved in the interfaces DP/DM and NoDP/DM by allowing for direct execution of desired system inputs through part (i.e., click-drag-drop mechanics) and subsystem manipulation. Direct manipulation produces a qualitative feeling of engagement allows agents to experience that their manipulation of the interface directly operates upon the objects of concern within the work domain (Norman, 1986).

A critical control function for a supervisory agent within the FMS work domain is to coordinate alongside or override the automated part production process ad hoc. The supervisory agent needs to control these expedition processes (i.e., part expedition, change WIP buffer capacity, change OP) in both a precise and expedient manner. The DP/DM and NoDP/DM interfaces support this need by providing metaphorical icons (e.g., parts) that represent these real-world objects directly. These metaphorical icons can be manipulated directly to adjust the FMS automated process.

In contrast, the DP/NoDM and NoDP/NoDM interfaces cannot be manipulated directly. Manipulation within the FMS STE requires the agent to execute command input through key-bound controls. The absence of direct manipulation resources can often lead to inefficient action sequences resulting in increased user error (due to slips and mistakes) and increased sequence time due to the essential properties of the indirect nature of decision implementation within the interface.

4.2.3 Visual Momentum

The design goal of visual momentum is supported in the DP/DM interface through various resources. System-related information from all five levels of the abstraction hierarchy (e.g., goals, functions, and physical components) is presented in a single, integrated viewing context, allowing for goal-related information to be immediately available in near-simultaneous view. The results suggest that the DP/DM interface leveraged powerful perception-action skills, thereby providing effective support for complicated and realistic domain tasks.

GENERAL DISCUSSION

Researchers in cognitive engineering (e.g., Norman, 1986; Rasmussen, 1986; Woods, 1991) have established structured, top-down approaches to identify work domain semantics. The different levels of the abstraction hierarchy correspond to different categories of information organized into five distinct categories describing high-level constraints, their corresponding low-level data, and the inherent relationship between them. The static form and dynamic behavior of a display must then map the semantics of the work domain (Bennett & Toms, 1993). The present results provide strong evidence that the CSE/EID framework can be used to design effective decision support for the flexible manufacturing system work domain. The DP/DM interface allowed for significant performance improvements (see Discussion section) for the majority of manufacturing tasks allowing for a continuous and "dynamic graphical explanation" (Hollan, Hutchins, & Weitzman, 1984) of the system state.

The concept that work domain constraints must be viewed independently of the interface or existing work practices is one of the major theoretical contributions of the CSE/EID approach (in contrast to, for example, traditional task analysis methodologies). As a result, it is important to distinguish between constraints inherent to the work domain and those built into it during the designing process. The outcomes of these work domain evaluations form the basis for interface design (i.e., EID). The results can then be translated into more efficient decision-making and problem-solving support utilizing design principles (e.g., direct vision, direct manipulation, and visual momentum).

Intent-driven domains (i.e.., BookHouse system; Pejtersen, 1992) often exhibit minimal consistency in their constraints, requiring intentions and goals on the agent's part to play a large role in the developing interaction within these socio-technical systems. Users will often demonstrate more heterogeneity and greater diversity in their domain-specific knowledge/skills (Bennett & Flach, 2011a), but a less comprehensive understanding of the decision support system (Talcott et al., 2007). In intent-driven work domains, the requirements for interaction can be more properly communicated (by leveraging preexisting concepts and knowledge) through the use of *spatial metaphors* to serve as signs representing various actions.

In law-driven domains (e.g., nuclear power plants), a high degree of constraint consistency is present. Law driven domains are categorized by their fulfillment of very specific goals (e.g., maintain energy balance) in a structured approach. Various system parts are tightly interconnected, resulting in a high degree of causality. The goal is to design representational aids that accurately reflect these physical and functional system couplings (Bennett & Flach, 2011a). The most effective design strategy for the mapping of constraints of law-driven domains is into analog geometrical forms (e.g., configural displays; Vicente, 1991; Bennett et al., 2008) to allow for a readily apparent view of the current system state (Talcott et al., 2007). In turn, this allows for the execution of powerful skill-based behaviors by the agent.

Intent-driven spatial metaphors are essentially self-contained, loosely coupled, aimed at representing familiar concepts and activities (Bennett & Flach, 2011a). In contrast, law-driven metaphors are highly dependent and tightly coupled, intended to communicate specific and accurate knowledge about the domain (Talcott et al., 2007). Flexible manufacturing systems' metaphors of interest have both characteristics, so the approach should selectively utilize both design techniques.

Gibson's (1966, 1979) concept of the perception-action cycle postulates that perception and action are unavoidably intertwined. The inclusion of an intact perception-action loop should be considered the highest goal in interface design to prioritize agents' use of perceptual-motor skills. In doing so, design should allow for the discovery of the affordances (presented through space-time signals) of the interface (direct perception of the icons) and coordination of control execution (direct manipulation of the icons; Talcott et al., 2007). Higher-order visual properties (i.e., optical invariants and optical flow) are specific to both the properties of the environment and the agent situated within it (over time). As such, to remove action is to remove one of the most fundamental properties of perception. Thus, one might expect the relationship between direct perception and direct manipulation in interface design to act in a similar manner.

The design strategy for perception-action icons selectively draws from these two categories (i.e., law-driven and intent-driven domains). The need for design strategy arises from the defining characteristics of the objects of interest in the FMS work domain. FMS resources are tangible contributors to meeting the overall goal of daily shift demands. However, this requires the consideration of individual products (i.e., parts): their number, type (A-G), and machining center operation requirements (1-3) to be completed on schedule. Information regarding resources and goal progress can be obtained collectively (through the production overview display) or individually (through specific icons).

A review of literature spanning several different disciplines appears to favor Gantt charts (Gantt, 1910) as the primary display choice in today's manufacturing system. Higgins (1996, p. 188) expresses why this is not a particularly good design choice, stating: "display for decision making must comprehensively show all data… to reveal all the relationships formed by the interplay of the data." The CSE/EID framework complements this goal. The principles of EID allow for the development of interfaces that assist with agent's ability to both safely and efficiently 'see' and 'explore' complex systems (through perception-action) for decision-making purposes (Flach et al., 2005; Flach et al., 2017).

Furthermore, a surprisingly large number of literature has argued against the CSE/EID approach to display design for flexible manufacturing systems. These criticisms range from the approach requiring minor or major changes (e.g., Upton & Doherty, 2006; Higgins, 1998, 1999) to outright rejection (Krosner et al., 1989) on the basis that the CSE/EID approach can only be successfully implemented in process control specific (law-driven) work domains. We, however, agree with Kinsley et al. (1994, p. 297) who state, "Despite a previous unsuccessful effort to apply the AH [abstraction hierarchy] … there are good theoretical reasons for believing that the applicability of EID is not limited to process control …" There is a continuum ranging from systems driven by user intents (i.e., intent-driven domains, e.g., using a mobile phone or searching the internet) to those where the laws of nature determine the unfolding of events (i.e., law-driven domains, e.g., process control). From the CSE/EID perspective, the difference between these two domains lies in the nature of their behavior shaping constraints. Despite the concerns regarding the utility of the CSE/EID framework for this work domain, the results of the present study suggest that the CSE/EID framework is well-suited for developing decision support in the (flexible) manufacturing work domain.

5.1 Conclusion

We investigated the effects of direct perception and direct manipulation on human supervisory performance utilizing a flexible manufacturing systems synthetic task environment. Significant results provide evidence that direct perception and direct manipulation in interface design produce an additive effect allowing for greater support of supervisory agents. Moreover, the application of either principle produced diametrically opposed patterns of results that provide very different answers to issues in display design. Performance was greater for dependent variables categorized as basic control activity when direct manipulation was applied to the interface compared to when it was not. Similarly, performance was greater for dependent variables categorized as work domain metrics when direct perception was applied to the interface compared to when it was not. Based on these results, designers should consider the potential influence of both of these principles in display design.

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