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Providing multiple 'ways in' to expertise for learners with different backgrounds: When it works and what it suggests about adult cognitive development

LIA DI BELLO

Center for Advanced Study in Education, CUNY Graduate School,
25 *West* 43 *Street*, *Suite* 620, *New York NY* 10036, *USA*

Abstract. The introduction of information technology into the workplace has changed the cognitive requirements for many categories of jobs. As a result, much emphasis has been placed on identifying the new basic skills and prerequisite knowledge for learning complex systems. In addition, because of the nature of the processes being controlled, some feel that a work history of shop floor experience may be more appropriate when decisions are made regarding who should use these information systems. However, these systems are notoriously difficult to learn for those who lack formal education. This study describes shop floor personnel successfully learning a management-oriented decision support technology while participating in an alternative educational workshop. The workshop itself and the follow-up evaluation of the participants suggest that identifying prerequisite knowledge may be unnecessary, or even beside the point, so long as the educational intervention is designed to accommodate multiple 'entry points' and permit constructive cognitive development rather than mere acquisition of procedures.

1. Introduction

With advances in technology, the normal divisions between 'manual' and 'intellectual' labour are collapsing; as more industries move towards mediating and controlling work using computerized tools, a greater number of workers at all levels are being compelled to conceptualize work and judge situations on a very different level of abstraction than before. In addition, because of the nature of the processes being controlled, a background in the details of a specific industry is often proving a better prerequisite for effective technology use than, for example, a background in computer systems or computer mediated management. For example, many industry leaders are pointing out that many so-called management systems fail because they are not being deployed at the shop floor level among workers with knowledge of actual processes. However, these systems are also proving difficult for many people to learn, regardless of background. The failure of shop floor workers to learn has only reinforced notions that they lack the necessary prerequisites for understanding complex technologies.

The study described in this paper concerns three levels of workers in a large remanufacturing facility learning the logic of MRP (Material Requirements Planning) systems. As will become clear, the important issues may not have to do with identifying who should or can learn these systems, but rather how learning occurs.

This specific study is part of larger programme of research begun at the Laboratory for Cognitive Studies of Activity at the CUNY Graduate School. The focus of our work concerns the cognitive impact of the introduction of technology into the

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workplace. Specifically, we are interested in exploring how workers' ways of thinking and understanding are affected by changes in the nature of work and workplace organization. Many of our questions have been addressed under a number of headings, such as 'novice–expert shift' (Chi *et al.* 1988) 'situated cognition' (Rogoff and Lave 1984), or 'naturalistic decision making' (Orasanu and Connolly 1993) and our work has been influenced by the methods and theoretical models from all of these various approaches. However, since the focus of our inquiry concerns the *development* of different ways of thinking in different domains, the research has been most influenced by the theories and methods of developmental psychology and particularly the developmental theories of Lev Vygotsky (1978, 1987).

Vygotsky's theory is an activity-based approach that has become increasingly influential on research in science and technology education (Davydov 1988, Hedegaard 1988, Martin in press, Moll 1990) as well as on studies of adult learning (Di Bello and Orlich 1987, Di Bello 1992, Glick in press, Martin and Scribner 1991, Scribner 1984, 1984a, 1985b, Scribner and Sachs 1990, Scribner *et al.* 1991) and, most recently, on those interested in organizational management and the distribution of knowledge in the workforce (Spender, in press).

The study described in this paper stems from early efforts at this lab to examine the relationship between school-based kinds of learning and 'experiential' learning. Traditionally, 'formal' knowledge, such as mathematics and physics, has been taught using a classroom-based method of instruction while 'informal' knowledge has been traditionally learned through experience, through on the job learning or apprenticeship. With the increasing use of 'formal' computer-based systems information flow and control in the workplace, more adults are required to learn 'formal' knowledge in 'informal' ways (Scribner *et al.* 1991).

Some of this early research focused on identifying the factors associated with learning MRP. MRP was selected as a domain because it represents a class of technology that is widely known to require users who have gone beyond procedures for operating the systems. Rather, effective use requires a deeper, more flexible understanding of the logic of MRP (in the sense described by Dreyfus and Dreyfus 1986 or Polanyi 1986) and there is a high failure rate because MRP is so difficult to learn. However, we do not consider our findings from these studies to be applicable only to MRP learning, but rather to the broader issue of learning complex technologies.

A description of one study will illustrate the intention of this early research and lay some groundwork for introducing the current study. We conducted a series of case studies of workers using MRP (Scribner *et al.* 1992) in two different factories (an electronics factory and a hardware factory), one with a successful MRP implementation and one with an unsuccessful implementation. In these studies, classroom instruction seemed to be uncorrelated with effective use of MRP (Scribner *et al.* 1991, 1992). Yet some individuals managed to master the systems. The study's goal was to define mastery in this domain as well as identify the factors that led to mastery. Not surprisingly, good 'book knowledge' of MRP and performing well on written tests were not associated with using the system well. In contrast, on-the-job activity proved to be critical to developing the necessary skills, and yet it was certain kinds of activity—not activity in general—that made the difference.

An analysis of day-to-day job activity by people in three 'titles' (planner, supervisor and expediter) and levels of responsibility revealed two distinct patterns of activity. The difference between these two activities is best characterized as 'constructive' and 'procedural'. Constructive activities are those that have clearly defined goals and poorly defined means. The employee is compelled to develop a procedure, form, tool or artifact which accomplishes the goal in an iterative fashion, obtaining feedback from more knowledgeable superiors only after attempting to develop a workable solution on her or his own. In contrast, procedural activities are those that have clearly specified means and order of execution, but goals which may not be clearly conveyed.

Importantly, constructive activities are associated with an in-depth understanding of MRP's underlying logic, and procedural activities are not, even if the employees perform essentially the same functions and even execute the same kinds of actions most of the time. In fact, when several variables—job title, years of experience, level of formal education and number of opportunities (per week) for constructive activities—were correlated with measures of in-depth grasp of MRP principles, only number of opportunities for constructive engagement was found to be significantly associated with mastery ($r = 0.69$ $p = \leq 0.01$); see Di Bello and Glick, 1993 for discussion). This study also showed that opportunities for constructive activities are usually fortuitous and ill structured. They often occur because the person who does know what to do has left the job without documenting procedures for others to use.

In the study described below, the relationship between 'constructive' and 'procedural' activities is further explored in an ongoing study of skilled manufacturing workers (individuals with expertise in the skilled trades) who are learning MRP at a very large re-manufacturing facility for commuter subway trains. This study differs in a number of significant ways from our previous work and from other research on employees using complex computer systems.

First, these workers were introduced to MRP in a two-day workshop that we designed. In our previous MRP studies we had not been able to observe learning as it occurred because the MRP systems had been in place at the time the studies were conducted. This railroad facility had no previous history of using MRP, had a largely traditional manufacturing operation and wished to implement MRP to deal with gross overspending on materials and a history of 'reactive' planning and purchasing. The facility allowed us to develop the training that workers would receive just prior to implementation. Given this opportunity, we designed a workshop that would engage workers with constructive and procedural activities in a more controlled way than normally occurs at work, using a hands-on simulation or 'game' that permitted participants to invent procedures for running a factory with MRP logic, but with little actual risk. This format allowed us to explore the relationship between 'constructive' and 'procedural' activities and learning. To ensure 'constructive' engagement, workers did not use an actual computer-based MRP system until the very end of training. Rather, they were given the tools to operate *as the system*, performing all its operations manually and making decisions about the contents of both static and variable data structures.

This study has another important feature. As indicated, increasing numbers of employees at various levels of an organization are required to understand complex systems but it is unknown how to design education for individuals with different backgrounds. In direct challenge to the notion that MRP and such systems require 'prerequisite' general formal education or computer experience, the training format did not differ for employees in different kinds of jobs. Rather, the simulation was designed to allow the participants to 'teach themselves' using a variety of activities and artifacts in ways that made sense to them. As will become clear, this may bring about a levelling effect that makes prerequisites unnecessary to identify.

One caveat: the MRP implementation at this facility has been problematic. A few months after installation numerous technical problems impeded full use of the system, and shortly after the first half year, a changeover in upper management threatened the entire project. The new upper management considered the system to be too costly and a nagging symbol of the 'old regime'. However, the implementation continues mainly due to insistence from those who had begun to use it. As will become clear, this is one case in which the developing skills of lower-level personnel affected policy decisions.

2. What is MRP?

MRP stands for a family of computer-based systems that integrates information from all aspects of a company's operations and uses it to make decisions (recommendations) regulating production and inventory.

MRP has been characterized as a theory of manufacturing. It instantiates certain key economic concepts such as *zero inventory* and *just-in-time* production and is based on principles of manufacturing (for example, formulas regulating how future orders are forecast) developed over the last several decades (Harrington 1974, Hendrick and Moore 1985, Timms and Pohlen 1970). Its objects and procedures are generically defined and the system is content-free until implemented in a particular plant. Its power as a predictor is contingent upon the data used (the content upon which the logic operates) and the extent to which its assumptions match the way things are actually made in a given setting.

Employees working with the system must translate the company's anticipated demand into a form that the MRP system can understand. This is done via a Master Production Schedule (MPS) which the system then interprets as a set of long-range, abstract production goals for the company's finished goods. With the information the system has on 'what' a particular finished good is (e.g. what parts go into it, what operations are involved, how long it takes to make each of its component parts and assemble it finally) it makes recommendations for every action leading up to the company's pre-set goals. This includes deciding upon start-dates and quantities for production orders and determining the most efficient pattern of purchasing. MRP is often relegated to the role of inventory database when (for whatever reason) employees cannot make use of its higher functions. In this case, its implementation is not considered successful by industry standards. As indicated in our previous work, 'success' in industry terms is highly dependent upon how well workers understand the system and its way of representing the products of their plant (Scribner *et al.* 1991).

There are three 'deeper' principles that organize the logic of MRP and mastery of MRP seems clearly related to grasping these organizing ideas. This is not surprising in that numerous studies in the literature on expertise point to the importance of underlying concepts (Chi *et al.* 1982). A full exposition of these principles is beyond the scope of this paper, but in order to make sense of the results, it is necessary to describe them here. First, MRP conceives of all parts, assemblies and finished goods as *hierarchically arranged items*, residing on 'levels' that roughly map onto how a given item is manufactured. Second, rather than using a linear, chronological representation of time, the timing of events is calculated beginning with a future date and moving back to the present. This is referred to as *phased time*. Third, quantities are not absolute, but time and item relative. When making enquiries about how many of a given part are in inventory, the system calculates a *virtual* or *relative quantity*, based on a number of time-sensitive factors. Although these principles seem quite simple on the surface, they organize the data and operations of MRP in ways that strike most people as counterintuitive and nonsensical. It is MRP's counterintuitive structure that makes it so difficult to use.

3. Method

3.1. *Participants*

Participants came from three job categories of the agency's Overhaul shop: Air Brake Maintainer (ABM) (unionized mechanics), Supervisors and Managers (salaried and non-union), and Analysts (a general office position for those involved in planning and special projects). All participants were drawn from a pool of employees who volunteered to participate in the MRP workshops. All of these volunteers expected to have their jobs affected by the planned MRP implementation and for many, our intervention would be their only form of introductory training.

ABMs are hourly employees who are trained mechanics with various backgrounds. About half of the participants entered the rail facility as 'car cleaners' after taking a qualifying civil service exam. They received their mechanical training through the facility's '18 month program'—a full-time training programme that instructs qualified applicants in air brake maintenance and repair. The other half had considerable mechanical work experience before coming to the shop and did not go through the 18 month programme. Many came from the aviation industry. ABMs are mainly responsible for disassembling, cleaning and remanufacturing the components of the air brake system and the compressor units. 'Officially' they are ignorant of the long-term schedule or plan for production. They are also not required to think about costs, material availability, consequences of inventory 'hoarding' or other work flow issues. However, observations of shop floor practices indicate that they are implicitly accountable for their material practices yet are not permitted the tools (such as access to computers or schedules) for anticipating future work demand. They get their orders in the morning and are required to do the day's work as issued by the foreman, in whatever manner they can.

Analysts do the official schedule, both short range and long range. Planning managers readily admit that these schedules are often not made in a coordinated fashion, and that there is no feedback mechanism for ascertaining whatever a given forecast or schedule was actually reasonable or not. This may account for the agency's practice of recycling purchasing and production schedules from year to year, whether they have actually met demand or not. In addition to the schedules, the analysts are engaged in the research necessary to acquire the materials needed for production and to meet changing safety regulations. They investigate new products, new designs for common items (such as door switches) and new vendors as well as identify the items needed and costs for various overhaul programmes or replacement programmes.

Supervisors and managers are required to keep the unionized hourly workforce occupied, schedule the needed skills on appropriate shifts, meet the schedule as it comes down from the planning department, and handle unplanned demand. They spend much of their time trying to find the materials that will help them actually meet the schedule and deal with various material shortages, usually created by poor schedules or unplanned demand (e.g. cars that break down or are involved in accidents). Since Overhaul is mainly reactive and crisis-oriented, it accomplishes its

Table 1. Pre-testing performance probes shown with the MRP core concepts targeted

Probe	*Core concepts: MRP*	*Core concepts: Manufacturing*
Scheduling item 'A'	Phased time* Hierarchical items Quantity per	Finished good/part Assembly process Horizon/Capacity
Card sort (carton of tacks)	Item structure*	Finished good/part Assembly process
Tree	Virtual Quantity* Quantity per	Finished goods/parts Min/Max On-hand quantity

* Targeted MRP concept.

goals at great financial cost, acquiring materials on short notice or overbuying in anticipation of unplanned demand of poor schedules. All participants were aware that the MRP system would be reorganizing the priorities of the shop to be more cost efficient and more oriented toward planning. Most were unclear about how their jobs would actually be affected.

3.2. *Pre-testing using performance probes*

Prior to participating in the workshops, each participant filled out a form with information on previous work history, formal education, computer experience and MRP experience. Subsequently, participants were interviewed about their current responsibilities and their notions of manufacturing, and were asked to do a number of performance probes that elicited their strategies in response to a manufacturing task. All these performance probes had been developed during earlier studies on MRP mastery. They had been thoroughly tested on actual MRP experts, identified with the help of various professional societies in manufacturing. The analyses presented in this paper are primarily from these performance probes, which are discussed in greater detail below. Generally, they were developed to tap into workers' understanding of key MRP and manufacturing concepts and were constructed to invite a variety of strategies. Table 1 lists the probes and which of the three underlying principles each targeted. Probes that tapped into more than one principle (unavoidable given the intertwined, embedded logic of MRP) were constructed to target one concept more strongly.

All interviews were audiotaped and participants were encouraged to talk aloud or explain their strategies to the interviewer while working.

3.3. *The pre-probes*

3.3.1. *Scheduling A*. 'Scheduling A' involved the scheduling of all production and purchasing activity to make 200 of a fictional, abstract item, for shipment in August. Participants were given a calendar, information about the item and all of its parts (including vendor and production lead times), a BOM (bill-of-material, the item structure file that defines an item in MRP), and certain constraining conditions. The participant was asked to write the complete purchasing, building and shipping schedule on the calendar and explain all decisions. The interviewer used a clinical method, asking the participant at various points the logic behind various scheduling decisions. A sample of the interviewer/interviewee dialogue is shown below.

> Interviewer: I noticed that you started in the August box and then started counting back. That's very interesting; why did you begin there?
> Interviewee: I am trying to allow enough time for the parts to arrive. I added up all the lead times from the BOM, and I'll begin on the date of the longest lead time.
> Interviewer: I see. What made you think of adding up all the lead times?
> Interviewee: Well, it doesn't make sense to start as early as January, to me. So I want to know what's the latest I can start and still have enough time.

3.3.2. *Card sort.* On this task, participants were asked to 'make an item' using a set of cards with the names and stock numbers of various components of a finished good. It was explained to the participant that all the cards represented a complete item and that the participant should use her imagination to arrange the cards into a sensible array representing the whole item and its parts. These cards did not represent a readily identifiable item—all that was clear was that it was made in a hardware factory and the codes and descriptions were from that factory's labelling system. As the participant sorted, the interviewer asked, again, for explanations and reasons for the strategy as it evolved. These conversations were recorded. At the end of the sort, the interviewer copied down the participant's array. All participants were asked if they wished to do it a second time, using a different strategy.

3.3.3. *Tree.* The tree question required participants to calculate the number of 'things' needed to complete an order of 20000 'A's, a completely abstract unknown item. This required participants to coordinate the notion of relative quantity with the notion of 'item'. There are three correct answers to this question and anyone who understands how MRP calculates is likely to give several of the possible quantities and the conditions that go with them. Again, participants were asked to give an answer (or more than one) and explain how the calculation was done and the logic behind it.

3.4. *Workshops*

The workshops used with participants were developed after months of analysis with the help of an MRP expert and others familiar enough with MRP logic to recognize activities and behaviour that most richly represented the core logic of MRP systems. In addition, observations of workers and interview data helped 'tailor' the activities to the participants at the rail facility. Below is a brief summary.

Although the activities and artifacts of the simulation workshop were carefully designed to promote 'constructive' activities in key conceptual areas, it was quite simple on the surface and was conducted in three phases over two days.

In general, participants were required to meet 'customer' orders by building three different models of a toy starship. They began with a fixed amount of cash, a foamboard partitioned 'stock room', limited quantities of parts, and various kinds of blank forms that could be used to organize and track the workflow. Each 'week' in the plant's schedule was 20 minutes long. Importantly, although they were told that to win they had to reduce inventory, increase profits and deliver a quality product on time, they were not instructed how. Rather, during the first morning of the two days, they were allowed to accomplish these goals in any way they wanted, using whatever tools or forms they found useful. During the second phase, participants analysed their results and the strategies as represented on forms, diagrams and researcher records.

From this activity they formed an explicit idea of their default strategies. During the third phase the game was played again, except now the participants were provided with MRP-oriented tools and forms and facilitated in the construction of a manual MRP planning system. Again, overall, they were not explicitly instructed. All sessions were audiotaped.

A true experiment would have used two workshop designs, one that contained mostly procedural activities and one that introduced the same ideas and concepts through constructive activities. However, this design also presented a risk that half the volunteers would be at a professional disadvantage after the workshops. Since this risk was unacceptable to our participants, the workshop was designed so that specific MRP concepts would be introduced through procedural activities for all participants, while remaining concepts would be introduced through constructive activities. Rather than compare conceptual change between individuals, conceptual changes in the three principal concept areas were compared within individuals.

Previous work in MRP learning shows that, of the three core concepts, the notion of ‘relative’ or ‘virtual’ quantity is acquired first while ‘phased time’ is acquired last and is reported to be the most difficult to grasp (Scribner *et al.* 1991, 1992). It would follow, that if constructive activities have a special capacity to shape development, then excluding constructive activities having to do with ‘relative quantity’ should alter this normally observed trend.

After considerable piloting, the workshop ended up including equal numbers of activities that would constructively engage participants with the MRP way of thinking about objects and parts (hierarchical items) and the MRP way of thinking about time (phased time). Considerable ‘procedural’ activities exposed the participants to concepts of virtual quantity and, in as much as it was possible, constructive activities exposing the logic of virtual quantities were avoided. This was difficult to do for two reasons. First, because of the intertwined nature of the core concepts in MRP, it is very hard to begin to understand phased time, for example, without getting a sense of how this will affect quantities. Second, MRP is very quantity-intensive; because all the mathematical calculations were done manually by the participants, actually ‘practice’ time with virtual quantity algorithms was probably greater than time spent practising activities related to other concepts. However, the workshops were carefully designed so that participants were not ‘constructing’ or inventing an algorithm for calculating virtual quantities. The lecture material and workbook text covered all concepts equally.

The idea here is that if constructive activity simply stimulates overall learning of all MRP concepts, the same pattern of acquisition seen in less structured environments (identified in other studies) should repeat itself, but may occur in less time. If constructive activities have a special effect, learning should be either a function of activity entirely, with no evidence of normally seen sequences or trends, or any sequences or trends would occur only with the conceptual areas that have been introduced through constructive activities.

The MRP system that the participants were getting in their shop was also installed at the university where the researchers were working. Once the system was installed, dial-in access was arranged so that the researcher could communicate via email with participants and observe any changes being made in their MRP system (such as the input of data, setting up of file structures, etc.)

Table 2. Post-test performance probes shown with the MRP core concepts targeted

Probe	*Core concepts: MRP*	*Core concepts: Manufacturing*
Scheduling item 'A'	Phased time* Hierarchical items Quantity (quantity per)	Finished good/part Assembly process Horizon/capacity
Scheduling Model 3 Starship	Phased time* Hierarchical items Quantity (quantity per)	(See above)
Scheduling button top pen (familiar, no activity object)	Phased time* Hierarchical items Quantity (quantity per)	(See above)
Card sort (Carton of tacks)	Hierarchical Item*	Finished Good/part Assembly process
Card sort (Starship)	Hierarchical Item*	(See above)
Tree	Virtual Quantity* Quantity per	Finished goods/parts Min/Max On-hand quantity

* Targeted MRP concept.

3.5. *Post-testing*

Post-testing was conducted about two months after the workshops. It was expected that by then any rote learning would be forgotten and MRP strategies exhibited by the participants would reflect what they had actually come to understand about MRP. As can be seen in Table 2, the post-performance probes were structurally similar to the pre-tests but applied to more kinds of objects. These tasks again elicited strategies that would reveal understanding of MRP and traditional manufacturing principles. This time, multiple versions of the scheduling and card sort tasks were given to ascertain how firmly the new knowledge had rooted and whether specifics from the activity with the starship would influence performance. The tasks were presented to various participants using a Latin Square order.

3.6. *Scoring*

The strategy elicited on each performance probe was scored for the presence, partial presence, or complete absence of twelve different strategies that have been shown in previous work to be associated with in-depth understanding of MRP principles. Protocols from each probe were also scored on five typical traditional manufacturing strategies. Coders were required to score a '1' if a particular strategy or behaviour was observed and a '0' if it was not. Each task protocol was given an 'MRP total' *and* a 'manufacturing total'. Table 3 shows some strategies that indicate MRP or traditional manufacturing thinking. Not all probes allowed the expression of all strategies (for example, the card sort did not afford any opportunity for 'back scheduling').

Table 3. Strategies associated with MRP and traditional manufacturing approaches, categorized by related MRP principle

MRP Strategies

Time:

1. Schedules backward from future date to closer future date
2. Begins with end item when scheduling end item *and* parts
3. Schedules parts beginning with level one items
4. Schedules levels sequentially (1, 2, 3, etc.)

Item:

1. Structures end items beginning with end item
2. Structures levels according to how object is made (things needed at the same *time* on the same level)
3. Structure is redundant, with the whole item re-represented *at least* on level one
4. Does not re-represent items that do not represent a re-stocked part

Quantity:

1. Quantity is calculated as 'quantity per' parent item
2. 'On hand' is physical count—allocated + scheduled receipt
3. Upper level components are used before lower level requirements are calculated
4. When lot sizes are not specified, purchasing and manufacturing are calculated as 'lot for lot' or one made to one needed
5. Demand/requirements are calculated before work is planned

Traditional manufacturing strategies

Time:

1. Schedules begin *now* with purchasing/work spread out evenly until due date (e.g. horizon method)
2. Begins scheduling with raw materials or 'ingredients'
3. Continues scheduling by moving 'bottom up' from raw materials to end items or may not schedule subassemblies separately from end items (e.g. time needed to complete end item may be an aggregate of all assembly times for sub-components of the item)

Item:

1. End item is comprised of its part; end item alone may not be represented
2. Structure (if any) looks like a routing with 'what's to be done' relationships rather than 'when to be done'
3. Structure is non-redundant and 'cluster-like'

Quantity:

1. Quantity is calculated as 'quantity per' end item
2. 'On-hand' is physical count
3. Requirements are calculated at each level using an 'aggregate' method (e.g. min/max)
4. Ordering is done in lots
5. Reordering is based on replenishment principles, and not demand driven

Scoring was based on the participants' pencil and paper work and their explanations for their strategies. Participants' explanations were used mostly to clarify ambiguous problem solving strategies. The coded forms of '0's and '1's were used for further analysis of overall strategy and patterns among sub-strategies. These analyses are described below.

Reliability of the coding scheme was tested using a blind coder, who had no familiarity with research of this kind, but was accustomed to scoring performance items (a clinical psychologist). Agreement between coders was 92% across all probes.

3.7. *Data analysis*

3.7.1. *Analysis of scheduling probes for evidence of MRP and manufacturing strategies.* The 'scheduling' tasks were designed to elicit the participants' overall MRP and/or traditional manufacturing strategy. These probes allow the participant the opportunity to do what manufacturing management systems actually do—schedule purchasing and shop floor activity for specific numbers of multi-part items in order to meet specific future deadlines. On each of the probes manufacturing and MRP strategies were scored as described above. Then for each task, the total number of traditional manufacturing and MRP-oriented strategies *each* were added (i.e., all the '1's) giving both an MRP total and manufacturing total. These numbers were then divided by the total number of possible strategies for each category, yielding a proportional score for each domain. For example, if a participant showed 8 out of 12 possible MRP strategies for a given task, the scorer would give him eight '1's and four '0's. To get the participant's proportional score, 8 is divided by 12, giving the participant a '0.67' for MRP, on that probe. The manufacturing score would be calculated the same way for the same probe. These scores rendered a gross picture of general strategy in each domain, or the replacement of Manufacturing strategies with MRP ones. From here on these are called the 'aggregate' MRP and Manufacturing scores because they deal with all the MRP or Manufacturing strategies used on a task, rather than particular MRP or Manufacturing strategies related to specific concepts.

As can be seen from Tables 1 and 2, the pre-test contained one generic scheduling question, to ascertain whether individuals had any MRP strategies at all. During post testing, three versions of this task were given: the original generic version (an abstract unknown object), a more complex version with the star ship (which the participant had extensive 'constructive activity' (experience), and an equally complex version with a common, familiar object—a button top pen (with which the participants had plenty of experience, but no 'constructive activity' history). Therefore, a total of four MRP and four Manufacturing scores were obtained for each person on scheduling probes.

A similar analysis was performed on the data from the card sorts (one pre- and two post-sorts). A total of three MRP and three manufacturing aggregate scores were obtained for each person on the card sorts.

3.7.2. *Analysis of data for recurring patterns.* Aggregate analysis of scheduling probes rendered information about overall growth, but not about specific patterns of strategies within tasks that might indicate shifts in understanding specific concepts. The '0's and '1's were re-analysed for recurring patterns.

The most striking of these was a tendency for some participants to do 'symmetrical' sorts when making item structures with the cards. Symmetrical item structures rarely occur in actual systems and these participants had never seen any examples of symmetry in item representations.

Table 4. Aggregate scores on scheduling probes, indicating overall MRP strategies on each task for each participant. Post-workshop averages do not include subjects who refused to complete one or more of the scheduling tasks

Subject	*Pre-test*	*Post*	*Ship*	*Button pen*	*Average post-test*
SUP1	0.25	—	0.83	0.66	0.75
SUP2	0.00	1.00	0.74*	0.08	0.58
SUP3	1.00	0.66*	0.63*	0.70	0.66
SUP4	1.00	0.58	0.66	1.00	0.75
Pre-workshop average for supervisors: 0.56 Post-workshop average for supervisors: 0.69					
ABM1	0.35	1.00	1.00	—	1.00
ABM2	0.00	1.00	0.75	0.58	0.78
ABM3	0.08	0.33	0.66	0.16	0.38
ABM4	0.41	—	—	—	0.00
ABM5	0.16	0.16	0.54*	0.66	0.45
ABM6	0.00	0.13	0.63*	0.66	0.47
ABM7	0.08	0.33*	1.33*	1.00	0.78
ABM8	0.16	1.00	0.66	0.58	0.75
ABM9	0.08	1.00	1.00	0.66	0.89
ABM10	0.08	—	0.87	—	0.87
ABM11	0.33	0.58	0.83	0.75	0.72
ABM12	0.00	0.58	0.58	0.64	0.60
ABM13	0.12	0.66	0.66	1.00	0.77
ABM14	0.12	0.58	0.70	0.63	0.64
ABM15	0.08	—	—	—	—
ABM16	0.08	0.08	0.08	0.00	0.05
ABM17	0.08	0.41	0.41	0.36	0.39
ABM18	0.16	0.63	0.66	0.55	0.61
Pre-workshop average for ABMs: 0.13* Post-workshop average for ABMs: 0.67					
ANL1	0.08	1.00	0.83	0.75	0.86
ANL2	0.16	—	0.41	0.20	0.31
ANL3	0.58	1.00	0.83	—	0.92
ANL4	0.16	0.37	—	—	0.37
ANL5	1.00	1.00	0.83	0.63	0.82
ANL6	0.25	1.00	0.75	1.00	0.92
ANL7	0.66	0.66	1.00	0.66	0.77
ANL8	0.58	1.00	1.00	1.00	1.00
ANL9	0.08	1.00	0.66	0.66	0.77
ANL10	—	0.58	0.66	0.66	0.63
ANL11	0.66	1.00	1.00	0.58	0.86
Pre-workshop average for Analysts: 0.42* Post-workshop average for Analysts: 0.75					

ANOVA comparing Analysts' and AMB's pre-workshop averages across tasks, $F(1,30) = 6.79$, $p < 0.001$.

Importantly, all cards carry sufficient information, in equally salient lettering, to allow them to be sorted correctly according to both their vertical and horizontal relationships to each other. A symmetrical sort is possible only if one ignores the 'goes into' information, which would indicate vertical relationships between that card and other cards. Figures 1 and 2 illustrate the difference. The data from the card sort coding forms for each participant were thus used to re-code for 'symmetry' patterns. Specifically, in the *re-coding*, participants' strategies were coded as 'Pre-sym' if a participant did not produce a symmetrical sort *because* the overall sort precluded any symmetry (e.g. they did a linear 'assembly' line sort with no levels). The sort was coded as 'Symmetrical' if they produced a symmetrical sort (resembling a pyramid) that *also* accurately represented each card's horizontal level, but with no regard to each card's relationship to those above and below it. The sort was coded as 'MRP-asymmetrical' if no symmetry was produced *because* the participant had used the vertical orientation information and was coordinating each card's vertical and horizontal relationship to the other cards. In other words, it was coded 'MRP-asymmetrical' if the sort was MRP-correct.

4. Results

A comparison of each participant's post-test performance with pre-test performance showed three trends. First, workers as a group showed that they were *replacing* their traditional manufacturing strategies with MRP-oriented ones rather than simply adding MRP strategies to their repertoire. Second, certain consistent patterns of error or misunderstanding indicate some support for the notion that participants were coming to understand MRP by constructing a kind of mental model of it and its relationship to real-world manufacturing and that this model underwent certain systematic shifts. In particular, some errors appear to be stage markers, predicting new levels of understanding about to emerge. Third, analyses of groups and individual differences showed that participants with different work histories may be coming to an understanding of MRP concepts through very different paths.

4.1. *Scheduling probes*

In general, traditional manufacturing strategies were replaced with MRP strategies after the workshops. This was shown most clearly on the 'scheduling' tasks. As noted in the Methods section, these probes invited the most comprehensive MRP and/or traditional manufacturing strategies. Tables 4 and 5 show aggregate MRP and Manufacturing performance scores from the scheduling probes for each participant and for each version of the scheduling probe. Table 6 presents a summary of the pre-workshop and post-workshop means among groups. As indicated in the Methods section, each participant received both an MRP and Manufacturing score for each task. Each of these aggregate scores represents the proportion of total possible MRP or Manufacturing strategies used to generate an answer. For example, a fully mixed (MRP and Manufacturing) *and* fully comprehensive set of strategies in each domain could result in an individual getting a 1.0 for both MRP and Manufacturing on the same task. These proportional scores are called 'aggregate' because they are calculated without regard to the pattern of strategies within a participant's performance, only their presence or absence.

Results in these tables show that overall knowledge of MRP concepts increased on

Table 5. Aggregate scores on scheduling probes, indicating overall Manufacturing strategies on each task for each participant. Post-workshop averages do not include subjects who refused to complete any of the post workshop scheduling tasks

Subject	*Pre-test*	*Post*	*Ship*	*Button pen*	*Average post-test*
SUP1	1.00	—	0.00	0.00	0.00
SUP2	0.80	0.00	0.70	1.00	0.85
SUP3	0.00	0.90	0.80	0.80	0.83
SUP4	0.30	0.00	0.00	0.00	0.00
		Pre-workshops average for supervisors: 0.52			
		Post-workshop average for supervisors: 0.42			
ABM1	0.80	0.00	0.00	—	0.00
ABM2	0.80	0.00	0.00	0.00	0.00
ABM3	1.00	1.00	1.00	1.00	1.00
ABM4	0.80	—	1.00	—	1.00
ABM5	1.00	1.00	1.00	0.54	0.85
ABM6	0.80	1.00	1.00	1.00	1.00
ABM7	0.80	0.80	0.40	0.40	0.53
ABM8	1.00	0.00	0.00	0.00	0.00
ABM9	1.00	0.00	0.00	0.00	0.00
ABM10	0.80	—	1.00	—	1.00
ABM11	0.60	0.00	0.00	0.00	0.00
ABM12	0.60	0.00	0.00	0.00	0.00
ABM13	0.80	0.00	0.00	0.00	0.00
ABM14	0.80	0.00	0.00	0.00	0.00
ABM15	0.60	—	—	—	—
ABM16	0.60	0.08	0.08	0.08	0.08
ABM17	0.60	0.00	0.00	0.00	0.00
ABM18	1.00	0.30	0.00	0.00	0.10
		Pre-workshop average for ABMs: 0.80			
		Post-workshop average for ABMs: 0.25			
ANL1	1.00	0.00	0.00	0.00	0.00
ANL2	1.00	—	1.00	1.00	1.00
ANL3	0.00	0.00	0.00	—	0.00
ANL4	1.00	0.60	0.50	0.50	0.53
ANL5	0.00	0.00	0.00	0.00	0.00
ANL6	1.00	0.00	0.00	0.00	0.00
ANL7	0.80	0.00	0.00	0.00	0.00
ANL8	0.00	0.00	0.00	0.00	0.00
ANL9	1.00	0.00	0.00	0.00	0.00
ANL10	—	0.00	0.00	0.00	0.00
ANL11	0.00	—	0.00	0.00	0.00
		Pre-workshop average for Analysts: 0.52			
		Post-workshop average for Analysts: 0.06			

ANOVA comparing Analysts' and AMB's pre-workshop averages for all tasks $F(1,30) = 11.31$, $p < 0.0001$.

Table 6. Average scores between domains for each occupational group, showing replacement of traditional manufacturing strategies with MRP strategies

	Pre-workshop		Post-workshop	
	Manufacturing	MRP	Manufacturing	MRP
SUPS	0.52	0.56	0.42	0.69
ABMS	0.80	0.13	0.25	0.67
Analysts	0.52	0.42	0.06	0.75

the whole while traditional manufacturing strategies diminished after the workshops. The differences between pre- and post-workshop scores were found to be significant for all workers, $F(1,30) = 6.79$, $p = 0.001$. In fact, the post-workshop scores were found to be somewhat higher than expected and comparable to those seen in plants where the system had been fully functioning for at least 2 years (Scribner *et al.* 1992). This is especially interesting given that many participants reported that they could not remember how they had approached this task before and could not replicate their previous strategy.

As can be seen by comparing Table 4 and Table 6, among the three job categories, supervisors began with the most initial MRP knowledge, as a group, but this was largely attributable to two individuals out of four. Analysts showed a wider distribution of relatively high initial MRP knowledge. Air Brake Maintainers averaged 0.13 before the workshops. An ANOVA comparing only the ABMs and Analysts indicate these groups differed significantly, $F = (1,28) = 11.3$, $p < 0.002$. (Given the small size of the supervisor group, they were not included in statistical analyses of between-group differences.) The tendency for analysts to show greater knowledge of MRP concepts, as a group, corresponds to their job responsibilities; many are planners and schedulers and some have worked in MRP environments before.

After the workshops, analysts showed higher average aggregate scores for MRP knowledge overall, averaging 0.75, with a median score of 0.82, but the least growth, given their beginning average. Air Brake Maintainers achieved aggregate scores somewhat lower than analysts after the workshops, with an average of 0.67 and a median score of 0.75. This was comparable to the average of MRP aggregate scores shown by supervisors (0.69). An analysis of variance comparing the ABMs and Analysts indicates that these post-test differences were not significant.

An analysis of variance comparing the Analysts' and ABMs' performance on the 'Abstract unknown' alone after the workshops did show significant differences between the two groups, $F(1,30) = 6.09$, $p < 0.02$. ABMs as a group seemed to have difficulty with 'post unknown abstract', which was a far simpler scheduling task (with three parts as opposed to the starship's 13 parts) but which was abstract rather than concrete or 'contexted'. When scores for this probe are not used in the calculation of averages ABMs averaged 0.71 and analysts averaged 0.75.

4.1.1. *Manufacturing strategies on scheduling probes.* On manufacturing strategies (see Table 5 and 6) Analysts averaged 0.52 before the workshops, while ABMs averaged 0.80. Supervisors averaged 0.53, but as can be seen in Table 5, they showed

Table 7. Aggregate scores for MRP strategies on card sorts indicating MRP scores on each task for each participant

Subject	*Pre-sort 'abstract unknown'*	*Post-sort 'abstract unknown'****	*Post-sort starship*	*Average post-score*
SUP1	0.00	0.75	0.75	0.75
SUP2**	0.25	0.75	0.75*	0.75
SUP3**	0.75*	1.00*	1.00*	1.00
SUP4	0.25	0.75	1.00	0.88
Average among supervisors Pre: 0.31; Post 0.84***				
ABM1	0.00	0.75*	0.75*	0.75
ABM2	0.00	0.50	1.00	0.75
ABM3	0.00	0.38	1.00	0.69
ABM4	0.00	0.50	0.75	0.00
ABM5	0.00	0.50	0.63	0.57
ABM6	0.00	0.00	0.00	0.00
ABM7**	0.50	0.50	0.75*	0.66
ABM8**	1.00	1.00*	1.00*	1.00
ABM9	0.63*	1.00*	1.00	1.00
ABM10	0.25	0.25	—	—
ABM11	0.50	0.50	1.00	0.75
ABM12	0.25	0.75*	1.00	0.88
ABM13	0.63	1.00*	1.00	1.00
ABM14	0.00	0.75	—	0.75
ABM15	0.00	0.25	0.63	0.44
ABM16	0.00	—	0.25	0.25
ABM17	0.00	0.75*	0.50	0.66
ABM18	0.50	0.75*	0.75*	0.75
Average among ABM's Pre: 0.24; Post 0.64				
ANL1	0.50	1.00	1.00	1.00
ANL2	0.00	0.75	1.00	0.88
ANL3	1.00	1.00	1.00	1.00
ANL4	0.50	0.75	0.50	0.63
ANL5	0.75	0.75	1.00*	0.88
ANL6	0.00	0.75	1.00	0.88
ANL7	1.00	1.00	1.00	1.00
ANL8	1.00	0.75	1.00	0.88
ANL9	0.00	0.75	1.00	0.88
ANL10	—	0.75	1.00	0.88
ANL11	0.75	—	1.00	1.00
ANL12	0.25	0.75	0.75	0.75
Average among Analysts Pre: 0.52; Post 0.89				

* Indicates 'integrated' MRP and manufacturing strategy.

** Indicates this subject's 'integrated' MRP and manufacturing strategy *co-occurred with classic MRP sort.*

*** ANOVA comparing groups on this task only, $F(2,30) = 5.03$, $p < 0.01$.

great individual variation. As before, significant differences were found between Analysts and ABMs on the pre-tests, $F(1{,}30) = 11.31, p < 0.0001$.

After the workshops, the average among ABMs was 0.25 (among participants who completed all tasks), while supervisors retained a relatively high 0.42 and analysts showed an almost complete absence of traditional manufacturing strategies (the mean was 0.06 among those who completed all tasks, and 0.13 including the two who did not). However, these differences between ABMs and analysts were not significant. In general, most participants showed diminished use of traditional manufacturing strategies and increased use of MRP-dominated strategies.

4.1.2. *Integrated strategies.*

A few individuals showed an interesting deviation from the trend towards replacement. These participants attempted to produce scheduling solutions that integrated both MRP and traditional manufacturing strategies. In Table 4, these results are marked with an asterisk. Those who attempted this consistently (on more than one post-workshop scheduling task) were Supervisor 3, and ABM7. (Supervisor 2 and ABMs 5 and 6 attempted 'integrated' solutions on the starship schedule only.) A closer look at their scheduling strategies reveals a rather sophisticated attempt to integrate plant and labour capacity considerations into the scheduling solutions. For example, although these individuals showed the 'backwards time' scheduling inherent in an MRP strategy, they attempted to spread out requirements evenly to accommodate plant or labour capacity. Capacity is one real-world aspect of scheduling that MRP cannot consider. In previous work, this kind of integration is an indication of rather sophisticated understanding of MRP concepts and the system's relationship to actual production and can take considerable time to develop (Scribner *et al.* 1992, Di Bello and Glick 1993).

Not surprisingly, the post-workshop interviews revealed that these five individuals were among seven who had begun to use the system at least on a weekly basis in a pilot project to schedule the work in their division of the Pneumatic shop (compressors). Observations indicate that these activities were largely 'constructive' as they involved setting up a new system without pre-set procedures. Supervisor 3, on the other hand, showed considerable MRP knowledge before the workshops and no manufacturing strategies (on the scheduling task). His subsequent experience with the system is not known.

Supervisor 3's profile suggests that replacing traditional manufacturing strategies with MRP strategies might precede integrating the two approaches. He moved from an MRP-dominated approach to a more integrated one. This may have been what occurred with ABMs 5, 6 and 7 and Supervisor 2 in the period between interviews, but there is no way to be sure. However, the profiles of these four do suggest that constructive activity after training might continue a general developmental trend begun in the workshops. This is further suggested by the complete absence of integration among the analysts, who have no opportunities for seeing how schedules are implemented on the floor. Unfortunately, the slowed progress of the system implementation did not allow us to examine the effects of on-the-job experience for more participants.

4.2. *Card sort tasks*

On the card sort tasks participants showed trends similar to those exhibited on the scheduling tasks. For most participants, MRP strategies came to replace traditional manufacturing strategies during post-testing. That is, rather than sort cards according

Table 8. Aggregate scores for traditional manufacturing on card sorts, on each task for each participant

Subject	*Pre-sort 'abstract unknown'*	*Post-sort 'abstract unknown'****	*Post-sort starship*	*Average post-score*
SUP1	0.50	0.33	0.33	0.33
SUP2	0.33	0.00	0.66*	0.33
SUP3	0.66*	0.50*	0.50*	0.50
SUP4	0.00	0.00	0.00	0.00
Average among supervisors Pre: 0.37; Post: 0.29***				
ABM1	0.66	0.41*	0.33*	0.37
ABM2	0.66	0.00	0.00	0.00
ABM3	0.50	0.41	0.00	0.21
ABM4	0.33	0.00	0.00	0.00
ABM5	0.66	0.00	0.00	0.00
ABM6	0.66	0.66	0.00	0.33
ABM7	0.50	0.50*	0.50*	0.50
ABM8	0.00	0.50*	0.00*	0.25
ABM9	0.50	0.50*	1.00	0.75
ABM10	0.50	0.50	—	0.50
ABM11	0.66	0.50	0.00	0.25
ABM12	0.50	0.25*	0.00	0.13
ABM13	0.41	0.33*	0.00	0.17
ABM14	0.75	0.00	—	0.00
ABM15	0.50	0.66	0.33	0.50
ABM16	0.50	—	—	—
ABM17	0.58	0.41*	0.58	0.50
ABM18	0.00	0.41*	0.75*	0.58
Average among ABM's pre: 0.49; post: 0.30				
ANL1	0.00	0.00	0.16	0.08
ANL2	0.50	0.00	0.00	0.00
ANL3	0.00	0.00	0.00	0.00
ANL4	0.66	0.00	0.00	0.00
ANL5	0.50	0.00	0.50*	0.25
ANL6	0.66	0.50	0.00	0.25
ANL7	0.00	0.00	0.00	0.00
ANL8	0.00	0.00	0.66*	0.33
ANL9	0.50	0.00	0.00	0.00
ANL10	—	0.00	0.00	0.00
ANL11	0.50	—	0.00	0.00
ANL12	0.16	0.00	0.41*	0.21
Average among Analysts pre: 0.32; post: 0.09				

* Indicates 'integrated' MRP and manufacturing strategy.

** ANOVA comparing all groups on this task only, $F(2,28) = 8.41$, $p < 0.001$.

*** ANOVA comparing all groups on average for all tasks, $F(2,28) = 4$, $p < 0.02$.

to traditional notions of goods either assembled from clusters of related parts, or related along a linear assembly dimension, participants were more likely to construct something like an MRP top-down hierarchy. However, the results from these tasks must be interpreted more conservatively as this probe tested mainly for participants' grasp of 'hierarchical item'.

Tables 7 and 8 summarize all the aggregate scores for all participants on MRP strategies and Manufacturing strategies, respectively (these were coded separately for the same task, as with the scheduling probes). Pre-test averages showed no significant between-group differences. During post-testing significant group differences were found between ABMS and Analysts on all overall averages for all tasks, $F = (2, 30) = 3.9$, $p < 0.02$. As with the scheduling probes, this difference was largely due to the analysts' greater average scores on the 'abstract unknown'. On this task alone significant between-group differences were found, $F(2, 30) = 5.03$, $p < 0.01$, while no significant differences were found with the starship card sort when it was analysed separately.

4.2.1. *Integrated card sorts*. As with the scheduling probe, card sorts revealed a few individuals with 'integrated' sorts. These sorts are marked with an asterisk on Table 7. Unlike integrated schedules, integrated card sorts are much harder to interpret, as they may reflect an incomplete understanding of MRP item structures and a tendency to default to manufacturing-influenced methods of classification. Because a scheduling probe incorporates all the major concepts of MRP (while the card sort merely taps into the concept of 'Item') it is much clearer when an individual is generating an integration of two approaches. Therefore, the protocols were examined again to see if the individuals who generated 'integrated' sorts had also generated a 'classic MRP' sort, showing understanding of MRP's item hierarchy (as noted in the methods section, each participant was given the opportunity to generate two sorts during each interview). Table 7 displays a double asterisk beside the identifiers of those individuals who generated a classic MRP sort during the interview and *also* produced the 'integrated' sort during their second attempt, as their preferred way of doing it. As can be seen when comparing Tables 4 and 7, these same participants were among those who had also generated integrated strategies on the scheduling probes (Supervisor 2, Supervisor 3 and ABM 7). As mentioned, Supervisor 2 and ABM 7 had been working with the system in a 'constructive' manner (setting up data files and defining objects and operations) in the period between interviews. Post-workshop interviews also revealed that ABM 8 had also been working with the system during that time. This further suggests the importance of constructive activities in the further development of MRP into an integrated understanding of MRP's relationship to production.

4.3. '*Error patterns*' *as stage markers*

Aggregate analysis of scheduling probes rendered information about overall growth of MRP strategies, but not about specific patterns among strategies (within a task) that might indicate shifts in understanding specific concepts. A closer analysis of the coded strategies on all probes revealed patterns that may indicate developmental stages. Three systematic error patterns suggested stage-like development 'within' concepts and, more importantly, that participants were 'constructing' MRP for themselves, rather than superimposing a transferred understanding. However, constructive activities maintained interesting effects. Because the subtleties of these patterns are difficult to appreciate for most people who are not expert in MRP, the most striking results—those having to do with the tendency of most participants to generate ‘symmetrical’ card sorts before fully grasping the notion of ‘hierarchical item’—are presented as a way of illustrating the general trend.

4.3.1. *Symmetry as it relates to concepts of hierarchical item structure*. The most robust error pattern showed up in a tendency for many participants to do symmetrical sorts when making item structures with the cards.

It seems that when participants first begin to understand the notion of items as organized according to hierarchical, redundant level structures, they grasp the item’s relationship to its *horizontal* level before they understand the relationships of items to each other, *between* levels, along a *vertical* dimension, even though both the horizontal and vertical orientations completely reorganize the way traditional manufacturing models represent item relationships. In traditional manufacturing, items are typically represented in a cluster relationship to the finished good. This partial understanding—grasping the horizontal but not the vertical—leads to an interesting systematic error in the card sorting task. Rather than sort the cards into an item hierarchy that considers both level and what the item is either going to become or go into, participants make symmetrical pyramids. Figures 1 and 2 show the difference between these two different sorting patterns. This is a particularly interesting result since the information needed to place the cards correctly (both vertically and horizontally) is clearly and equally represented on the cards. Subjects seem to be ignoring the ‘goes into’ information while attending to the ‘level’ information. This is also interesting because such symmetrical ‘pyramids’ are virtually non-existent in actual MRP structures and there are none in the participants’ workshops, training materials or work materials. In other words, they are invented by the participants.

Table 9 shows the percentage of all participants exhibiting symmetry or asymmetry on pre- and post-workshop card sorts. These figures show the ubiquity of this pattern. Close examination of individual profiles strongly suggests a transitional function for symmetry. In nearly all individuals, symmetry occurs as a precursor to grasping the

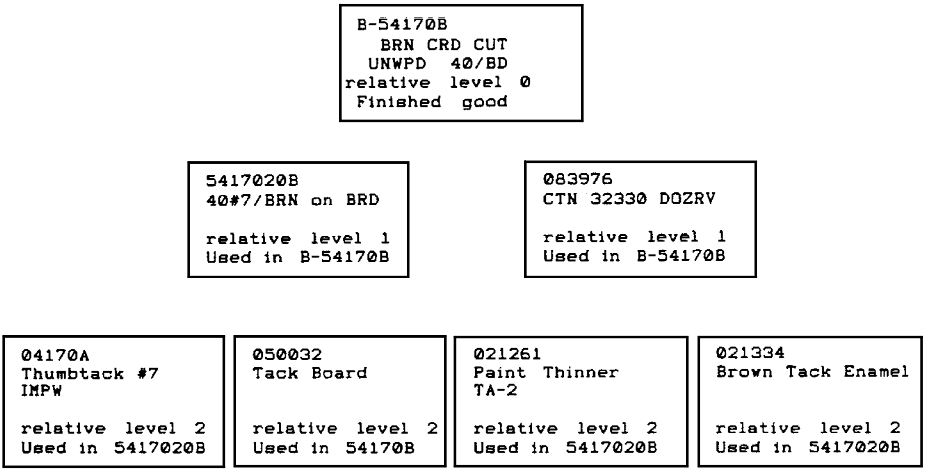

Figure 1. Symmetrical sort.

vertical dimension of item relationships in item structure. For example, if a participant sorted symmetrically on her pre-test (showing a horizontal but not vertical understanding of levels), in all cases this error was resolved by the time of the post-test. In participants who showed no notion of item structure in pre-testing, the notion first appeared as a symmetrical sort. This sequence was never reversed in any individual's data (although one participant reverted to symmetry on one post-workshop card sort, and not the other). See Table 10 for the sorting patterns across all card tasks and percentage of participants that exhibited each pattern. A χ^2 comparing the patterns of invariant and variant sequences among all participants with the expected even distribution of invariant and variant sequences among a group of the same size was highly significant ($p < 0.00001$).

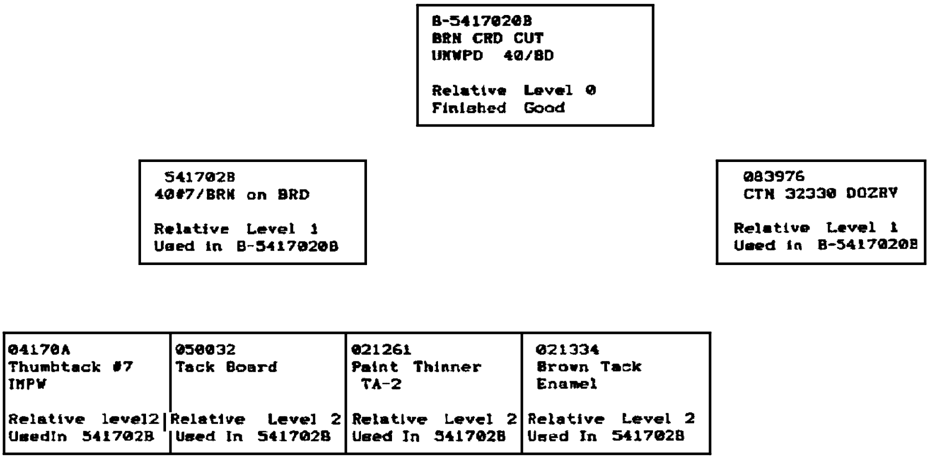

Figure 2. MRP asymmetrical sort.

Table 9. Overall percentages for symmetry/asymmetry and 'non-level' performance on 'card sort' probes for all subjects, all card sort tasks

Type of answer	*Pre-test card sort 'unknown' object*	*Post-test card sort 'unknown' object*	*Ship card sort 'Starship'*
No level understanding*	61%	16%	9%
Symmetry (horizontal level)**	24%	62%	12%
Asymmetry vert. and horizontal***	15%	22%	79%
N =	34	32	34

* The subject produced a sort with no MRP-like item structure represented at all, e.g. usually an assembly sequence was constructed.

** The subject sorted cards by level only *and* formed a symmetrical pyramid with the cards.

*** The subject arranged cards in a classic MRP Item structure, coordinating 'level' information with 'goes into' information for all cards.

Table 10. Observed sorting patterns among all subjects showing invariant sequence from symmetry to asymmetry on the three card sort probes

Percentage of subjects		*Pre-test card sort*	*Post-test card sort*	*Ship card sort*
%	*N*			
8.5%	(3)	0	0	0
8.5%	(3)	0	1	1
40%	(14)	0	1	2
0%	(0)	0	2	2
11%	(4)	2	2	2
8.5%	(3)	1	2	2
8.5%	(3)	1	1	2
3%	(1)	0	0	2
3%	(1)	1	…	2
3%	(1)	0	…	1
3%	(1)	0	0	…
3%	(1)	2	1	2*

* Indicates only case of non-sequential progression.
… Indicates refusal to attempt task.
0 The subject produced a sort with no MRP-like item structure represented at all, e.g. usually an assembly sequence was constructed.
1 The subject sorted cards by level only *and* formed a symmetrical pyramid with the cards.
2 The subject arranged cards in a classic MRP item structure, coordinating 'level' information with 'goes into' information between all cards.

Most interesting however, are the differences in symmetry behaviour between the two *post-test* card sorts. One card sort represented an unknown object, abstractly represented and impossible to identify (the item from the hardware factory, shown in Figures 1 and 2). The other represented the starship that participants built and invented planning methods for during the workshop. Both sets of cards contained the information needed for horizontally and vertically correct MRP sorts. Table 9 shows that among 47% of the participants, symmetry occurred when sorting the unknown object, while a completely correct sort was performed for the ship, suggesting that these participants could only exhibit their full understanding of 'item' with the object they had learned MRP through.

In most cases, participants were not aware they were using different strategies, or if aware, could not correct the symmetry in the unknown object even though they knew what information was important! The example dialogue below illustrates this discrepancy. The excerpt is from a protocol of an analyst who produced a symmetrical sort on the abstract unknown task, and an MRP-correct sort on the starship task.

> ANL3: (after sorting the 'unknown object' cards symmetrically) I know that's not quite right, but I don't know why.
> EXP: Well, I don't think you did the starship cards the same way. Were you thinking different things?
> ANL3: Yeah, I mean, I know I should do something different, Level, one, level two, that's all right.
> EXP: Maybe it has something to do with the other information on the cards.
> ANA3: Yeah, I know, but I don't know what to do different.

Table 11. Differences in overall performance on three core concepts. Data from tree, scheduling and card sort probes. Percentages represent proportion of subjects with strategies showing full grasp of the principle involved

	Relative Quantity	*Phased Time*	*Hierarchical Item*
Pre-test	*0%	**12%	****15%
Post-test	*6%	**48%	****22%
Post-test ‘Starship’ task	*NA	***74%	*****79%

* Tree Virtual Quantity probe.
** Phased time analysis from ‘scheduling abstract unknown’ probe.
*** Phased time analysis from ‘scheduling Starship’ probe.
**** Hierarchical item analysis from ‘unknown object card sort’ probe.
***** Hierarchical item analysis from ‘Starship card sort’ probe.

There was *never* a case in which symmetry was exhibited on the ship while a horizontally and vertically correct sort was exhibited on the unknown object. In only three cases (8%) were symmetrical sorts performed for both objects.

Of the eight participants performing symmetrical sorts *before* training, only four failed to resolve the conflict on the post-test for the unknown object, although all had resolved it for the ship and produced correct sorts on that task.

4.3.2. *Uneven change in the three organizing principles.* The results so far have been on specific probes. The following analyses and results concern patterns of response across the performance probes. It is clear that all participants changed and moved toward increasingly ‘MRP-like’ strategies, and in some cases a sophisticated integration developed. As will become clear, examining patterns across probes reveals that constructive activities have specific effects on the development of concepts.

As predicted, the learning did not occur evenly among areas covered by the workshop. The workshops were constructed to provide extensive practice with the notion of ‘relative quantity’, but participants were given specific MRP calculation procedures and were not encouraged to invent or explore MRP algorithms for obtaining virtual quantities. In other work, ‘virtual’ or ‘relative’ quantity is usually shown to develop first among the three organizing principles, and is generally considered the ‘easiest’ MRP notion (Scribner *et al.* 1991) whether learning is incidental or classroom based. This did not happen here—in fact quantity was the weakest—suggesting that constructive activities can influence the concepts that develop.

Table 11 shows relative performance in the three conceptual areas and the probe data scored. These data are percentages of participants, taken from several probes as noted. As can be seen, the fewest participants achieved a truly flexible notion of Virtual Quantity. In addition, all participants who came to understand Virtual Quantity also developed a thorough understanding of Phased Time and Hierarchical Item while many who became adroit with Phased Time and Hierarchical Item did not come to understand Virtual Quantity.

4.4. *Understanding of Virtual Quantity, as measured by the* ‘*tree probe*’

Subjects’ lack of development with ‘virtual quantity’ is further shown in their

Table 12. Answers to 'tree' quantity question. Percentages show frequency of each possible answer among subjects

	Pre	Post
Adds all: 180000	89% (31)	47% (16)
Grasps partial redundancy with quantities: 140000***	6% (2)	12% (4)
Grasps full redundancy: 120000***	6% (2)	35% (12)
Can give a variety of correct virtual quantities****	0%	6% (2)
N =	35	34

* Indicates no concept of how MRP calculates quantities—a typical traditional manufacturing strategy.

** Indicates that the subject realizes that *some* of the parts on the tree are actually subassemblies of other parts and need not be counted twice.

*** Indicates that the subject realizes every part that undergoes some change before the final assemble need not be counted twice, but being able to give *only* this answer indicates that the individual does not yet realize that the 'what' that gets counted can be relative and a variety of answers are possible.

**** Indicates a fully flexible notion of virtual quantity.

performance on the 'tree' probe, a performance task much used in previous MRP studies and designed to test for understanding of how MRP calculates Virtual Quantities. Table 12 shows the performance of participants on the 'tree' probe, which measured participants' ability to calculate a variety of Virtual Quantities. Table 12 shows all the possible calculations for this task and the percentage of participants who gave each answer. 'Adds all = 180000' indicates no concept of how MRP calculates quantities and indicates a typical traditional manufacturing strategy. 'Grasps partial redundancy = 140000' indicates that the individual realizes that some of the parts on the tree are actually assemblies of other parts and need not be counted twice. 'Grasps full redundancy = 120000' indicates that the participant realizes every part that undergoes a change before the final assembly need not be counted twice, but being able to give *only* this answer indicates that the individual does not yet realize that the 'what' that gets counted can be relative, and a variety of answers are possible. 'Can give a variety of correct virtual quantities' indicates that the participant realizes that there is no one answer to this task and in fact several answers are possible. This indicates a fully flexible notion of virtual quantity. As can be seen, only two people were able to do this during post-testing (6%).

4.5. *Overall 'concept profiles'*

Uneven development is also shown in patterns of concept acquisition among the participants across several tasks. Table 13 shows these patterns. The percentages shown indicate the percentage of participants who possessed a specific profile of concepts. As can be seen, only 6% showed full proficiency for all concepts on all tasks, although 15% showed full proficiency on components of all probes having to do with both Phased Time and Hierarchical Item. More importantly, all those who developed

Table 13. Patterns of mastery among the three MRP principles exhibited by subjects across performance probes

Full mastery of core concepts as indicated on strategies. Percentages refer to subjects

	Pre-tests*	Post-workshop** (%)	Post-workshop (Starship tasks)*** (%)
Q only	0	0	0
T only	0	0	0
I only	0	5	0
QI only	0	0	0
TI only	0	15	16
QTI	0	6	7

Partial mastery of core concepts

	Pre-tests*	Post-workshop** (%)	Post-workshop (Starship tasks)*** (%)
Q only	0	0	0
T only	0	0	0
I only	0	0	0
QT only	0	0	0
QI only	0	0	0
TI only	4	10	34
QTI	5	45	35

* Tasks used: Pre-probe tree (quantity), card sort (item), scheduling abstract unknown (Time and item).
** Tasks used. Post-probe tree (quantity), card sort (item), scheduling abstract unknown (Time and item).
*** Tasks used: Post-probe tree (quantity), starship card sort (item), starship scheduling (Time and item).

the concept of Virtual Quantity also developed an equal understanding of Time and Item concepts. Many who showed an impressive understanding of Time and Item did not develop commensurate Quantity concepts.

5. Discussion

It is clear from the post test results that two months after the 'constructive' activity training workers performed at a level of mastery that is normally seen in workers who had managed to learn to use the system effectively at other sites after 18–24 months. More importantly, workers exhibited these strategies spontaneously and appeared to have replaced old ways of solving the same problems with new approaches. In other words, knowledge was reorganized rather than added. Some participants reported that they realized they had done it differently before but could not replicate or remember their previous approach.

Their performance on the floor supported these results. Even though the MRP implementation came to a crisis when upper management was replaced, shop floor personnel who had system access made use of the system to manage their own work areas, instructed management personnel in MRP, and took upon themselves the tasks of data entry and system upkeep. Although the implementation continues to be problematic in this facility, it is widely agreed that its problems are not related to worker skill. Rather, worker skill has compelled the new management to maintain the system.

The question remains—how did constructive activities effect this transformation?

It appears that constructive activities permit individuals to reorganize the implicit mental models which are driving the decision process. A description of what typically happens during the workshops will illustrate this point. During the first morning of the workshops the teams of participants must 'run' their factory in any way they choose so long as they meet the customers' orders on time, honour production lead times and pay the vendor on delivery for the materials or parts they purchase.

Without exception, under this kind of pressure, all groups default to the strategies they normally use at work. Comparing performance in the workshops with job function indicates a strong correspondence between current work practices and decisions under pressure. For example, teams of mechanics almost always deliver a high quality product on time and thereby manage to stay financially above water by ensuring income. However, they do so often by buying finished assemblies (as opposed to raw materials) at great cost, by accelerating production (which has the real-world consequence of 'overtime'), and by overbuying all materials. Thus, they sacrifice profits. In contrast, teams of analysts and managers are often *not* successful at meeting customer orders or the poor quality of their work causes orders to be refused by the 'customers'. However, they are very hesitant to overspend; often they cannot meet orders because they have waited too long to decide to purchase the necessary materials. Individuals resort to these default strategies even when they are *explicitly instructed* to operate differently and when they are aware that the goal of the game is to make the most profit and buy the least material.

During the workshop's first pause participants fill out forms, evaluate their net worth—calculating worth of material, WIP (Work in process), cash and subtracting debt, damaged material and lost opportunity—and compare their production schedule and financial situation to an 'MRP ideal' generated by a computer. During the discussions that follow the self-evaluation, participants begin to reflect upon these default strategies and examine how a different approach might have accomplished their goals. It is only at this point that participants realize what assumptions have been guiding their decisions under pressure and with what results. We have come to call this the deconstruction phase and the beginning of reorganization. During the MRP-oriented 'constructive' activities that follow in next day and a half, participants continue a pattern of inventing a solution using their intuitive understanding of manufacturing, noticing its mismatch with their goals, reordering what they've done and comparing it again to their goals. At the end of this process, all participants arrive at the *same solution* but the data suggest they have all done so via *different paths* and have begun the process through sometimes radically different entries.

It seems that constructive activities work—and work for a wide variety of people—because they are both multi-modal and self-modal. They permit a variety of entries to knowledge and they permit the individual's entry to be in terms of his or her existing way of thinking in that domain. Rather than overlaying existing knowledge, constructive activities permit the reorganization of knowledge that occurs when learners are compelled to bring their current way of thinking to bear on the problem, notice its mismatch with desired outcomes, and make refinements in accordance with the tools they are discovering (in this case MRP).

To further illustrate, let us return to some of the differences found between the workers on the post-tests. First, although there were no significant differences between the ABMs and Analysts on aggregate performance, differences in their patterns of response on different probes indicate they were 'coming to' the same notions through different means. For example, on the 'scheduling' tasks, almost all of the variance in average aggregate MRP scores was due to performance on the abstract unknown probe. Although this task was much simpler than the same probe using the starship or pen (3 parts as opposed to 13 parts with various lead times), the mechanics exhibited the most sophisticated strategies with the more complex, but identifiable objects. The paradox of the more complex (but more concrete) being simpler for one class of participants suggests interesting possibilities. It seems as though this group was not oriented to approaching problem solving when the context was presented abstractly although they were capable of thinking abstractly and symbolically about contexted objects. Conversely, the analysts were able to take better advantage of the simplicity of the 'abstract unknown' and were more likely to make calculation errors on the starship task. This result is particularly interesting given that abstract problem solving is sometimes thought to be more sophisticated than concrete or contexted problem solving.

The mechanics' ability to operate with the complex but concrete makes sense given their jobs. They are required to work with highly complicated assemblies containing hundreds of small, but essential parts. In order to perform well on the job they must pay attention to tiny details, and to the potentially dangerous impact of small assembly errors. It may be that the requirements of their jobs have oriented them to grasp general relationships or concepts through the specifics, while at the same time making them more able to handle a large amount of detail in parallel. The differences between the ABMs and the analysts support the more general notion that job-specific ways of thinking may influence ways of learning, and that activities or learning situations that permit multiple ways to attend to information and concepts may erase normally observed group differences in overall ability to learn.

Another illustration is provided by the effects of the 'procedural' activities. Despite considerable practice with MRP's methods of calculating virtual quantities as well as plenty of explanation and simplified examples, all but two participants (see Table 4) defaulted to their previous methods of calculating quantities during the post-probe interviews. In other words, no 'replacement' took place for most when it came to quantity strategies. Clearly, hearing concepts explained and even practising formulas for hours did not engender real change or in-depth understanding. Rather, this result suggests that learners must construct for themselves and according to an individual entry point.

6. What constructive activities suggest about developmental mechanisms

We are still left with the unanswered question of mechanism. The fact that constructive activities permit the construction of knowledge from multiple entry points is, in itself, not compelling unless we consider why and what this might reveal. If we consider constructive activities in view of the reported error patterns which tended to be orderly and sequential, more is revealed. Re-examining the nature of the errors shows that, in general, participants were both 're-creating' MRP principles for themselves, and doing so by appropriating the surface features first, and getting the more subtle aspects later. This is especially true of the tendency towards symmetrical sorts, which are a kind of simplified reconstruction of the MRP notion of hierarchy but which have no basis in actual MRP systems. Such sorts seem to derive from most adults' experience with superordinate and subordinate category systems and perhaps this gross similarity was noticed first. The pattern suggests that adult learners learn by constructing and re-creating the domain for themselves *in any case*, and assimilate structures from other learning in order to do so, focusing first on surface or gross similarities.

Constructive activities seem to take advantage of this tendency and rather than work against it, work with it. Rather than attempting to push old knowledge out of the way, constructive activities may permit it to be used as fodder for developing a new way of thinking the same old things. This may explain why, in part, there was *replacement* rather than addition for some of the participants who tried to recall their previous way of doing things. If the reorganization takes place at the level of what is spontaneously and intuitively drawn upon, it may be that the original model of things is so changed it is lost in its original form, much like Piaget's notion of *dépassement*.

On the other hand, the scant data from the participants who showed a more 'integrated' approach suggests that, when they resume real world problem solving, the 'old' model may reassert itself somewhat, but in a form that incorporates MRP ways of thinking. In other words, after the workshops workers may resume their duties with a marked 'MRP bias', but with experience, their thinking becomes more integrated. The complete absence of an integrated approach among analysts (who have no hands-on manufacturing experience after the workshops) and Supervisor 3's profile (which showed a marked MRP bias changing into an integrated approach) support this notion, but the data from this study are too scant to draw any definite conclusions.

Although this paper presents only a small portion of a huge corpus of data—with much potential for further analyses—it makes a compelling case for rethinking education for adults who already have considerable skills. These results suggest that the 'default' modes or intuitive understanding that is developed with experience may act as both an impediment and bridge to learning new technologies in one's domain of expertise. Constructive activity-based instruction may offer a way to make an impediment into a bridge without sacrificing current experience and expertise.

In addition, the results presented here and the subsequent proficiency in MRP shown by the participants' on-the-job performance interrogate traditional notions of technology training, prerequisite knowledge and technology deployment. It seems that complex systems can be handled well by those who are normally not considered eligible users/learners. Perhaps the efforts to classify learners are better directed toward developing a more thorough understanding of how learning occurs among work-experienced adults.

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