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Learning, communication, and the bullwhip effect

Diana Yan Wu, Elena Katok *

Smeal College of Business, Penn State University, 509H Business Administration Building, University Park, PA 16802, USA

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Abstract

We investigate the effect of learning and communication on the bullwhip effect in supply chains. Using the *beer distribution game* in a controlled laboratory setting, we test four behavioral hypotheses – bounded rationality, experiential learning, systems learning, and organizational learning – by systematically manipulating training and communication protocols. We find that order variability decreases significantly in a setting in which participants start with hands-on experience, and are then allowed to formulate team strategies collaboratively. This result indicates that while training may improve individuals' knowledge and understanding of the system, it does not improve supply chain performance unless supply chain partners are allowed to communicate and share this knowledge. Our results indicate that the bullwhip effect is, at least in part, caused by insufficient coordination between supply chain partners.

Keywords: Bullwhip effect; Supply chain management; Experiential learning; Systems learning; Organizational learning; Communication; Experimental economics

1. Introduction

Supply chain management is an example of a dynamic decision task that involves lagged feedbacks and multiple dependent decision makers. This task is known to be difficult for several reasons. According to Sterman (1989a), when decisions have indirect and delayed feedback effects decision makers find it difficult to control the dynamics. Moreover, multiple agents are involved in the process, whose performance depends on the quality of other supply chain members' decisions, and therefore is subject to coordination risk that may trigger instabilities in the system (Croson et al., 2005). One well-known inefficient outcome produced is the much studied *bullwhip effect*.

The bullwhip effect refers to the observation that the variability of orders in supply chains increases as one moves closer to the source of production. The effect is costly because it causes excessive inventories, unsatisfactory customer service, and uncertain production planning. According to Lee et al. (2004), several industry studies such as efficient consumer response (ECR) and efficient foodservice response (EFR), report the bullwhip effect as most harmful to the efficiency of a supply chain. The bullwhip phenomenon was first noted by Forrester (1958), and has since been observed in many diverse settings. For example, Hewlett-Packard found that orders placed to the printer division by resellers have much bigger fluctuations than customer demands, and the orders to the company's integrated circuit division have even worse swings (Lee et al., 1997). A wide range of industries, including computer memory chips (Fisher, 1994), grocery (Fuller et al., 1993), and gasoline (Sterman, 2000), has experienced similar symptoms.

Previous research on the bullwhip effect thus focuses on understanding of its causes and ways to alleviate it.

* Corresponding author.
E-mail address: ekatok@psu.edu (E. Katok).

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Two categories of explanations have been advanced. Lee et al. (1997) identify four *operational* causes of the problem, including errors in demand signal processing, inventory rationing, order batching, and price variations, and recommend a number of operational strategies for dampening the effect.

The second category focuses on the *behavioral* causes of the effect. Behavioral causes are usually studied in the laboratory because it provides ways to eliminate operational causes, which is impossible to do in the field. The existence of the behavioral causes of the bullwhip effect has been demonstrated in a variety of laboratory settings and by many different researchers (see for example, Sterman, 1989a,b; Croson and Donohue, 2003, 2004; Croson et al., 2005). These studies consistently show that participants do not adequately account for the time delays in making ordering decisions, and specifically, they tend to under-weight their *supply line*, orders placed but not yet received. Hence, the first behavioral explanation emphasizes the individuals' bounded rationality to control systems with lagged, indirect and nonlinear feedbacks (Sterman, 1989a). More recently, Croson et al. (2005) identifies another behavioral cause based on *coordination risk*, the uncertainty about the actions of other decision makers, and show that it often triggers instability.

The controlled environment of laboratory also enables us to explore and isolate the impact of *institutional or structural* changes to the supply chain on mitigating the bullwhip behavior. Innovations such as reducing ordering and shipping delays (Steckel et al., 2004), providing additional inventory information (Croson and Donohue, 2004), sharing point-of-sale information (Steckel et al., 2004; Croson and Donohue, 2003), and adding excess inventory to the system (Croson et al., 2005), all improve performance in the laboratory.

In this paper, we further delve into the causes of supply chain instability, and look at the problem of the bullwhip effect from an *organizational learning* (OL) perspective. The concept of OL was first introduced by Cangelosi and Dill (1965) and has dominated the management literature in the 80 and 90 s. The general consensus on theories developed in this area is that learning occurs at multiple levels (Crossan et al., 1995): *information* is processed and transformed into *insights* and innovative ideas by individuals first (Simon, 1991); then knowledge is shared and mutual understanding is developed among groups (Huber, 1991; Lant, 1992; Stata, 1989); and some individual or group learning further become institutionalized as organization artifacts (Crossan et al., 1999; Shrivastava, 1983).

Some recent research efforts have been made to apply the OL paradigm to supply chain management, recognizing its competitive advantage on improving supply chain relationships (Bessant et al., 2003; Hult et al., 2003; Preiss and Murray, 2005). In this study, we view the supply chain as an integrated organization and investigate the effect of learning on alleviating the bullwhip symptoms. More specifically, as the unifying framework by Boudreau et al. (2003) proposed to bring human resource management considerations into operations management context, we examine to what extent *training* and *communication* impact the local ordering decision-making process and the global learning and behavior of supply chain as an organization. To study this question we take advantage of the controlled laboratory setting.

We conduct the study within the context of the *beer distribution game*, a simulated serial supply chain with four links (see the next section for details). This game is popular in supply chain management classes and has also been used extensively in the experimental research we cite above. In order to increase control and provide the most rigorous test of the behavioral theories of the bullwhip effect, we modify the standard design in two ways for all of our experiments: (1) we use a stationary distribution for customer demand which eliminates all operational causes of the bullwhip effect, and (2) to facilitate individual decision-making, we *directly* display for each participant information about his own supply line (or *outstanding orders*), which has not been made visible in prior studies.

So as to examine the role of human activities on one's judgment in the simulated environment, we relax some traditional game protocols. First, instead of using participants with little or no experience, in some of the sessions we provide participants experiential training with the beer game to promote individual learning and counteract possible decision biases. One of our manipulations is how this extra hands-on experience is structured: in some of the treatments participants practise in a specific role assigned to them, which we call *role-specific training* since it allows participants role-constrained learning experience (March and Olsen, 1975). In other treatments participants practise in the role of central planners making decisions for all members in the supply chain, and we call this condition *system-wide training* since it permits *systems thinking* that directs attention to underlying systemic interrelationships (Checkland, 1981; Senge, 1990; Senge and Sterman, 1992; Jackson, 1995). We also include treatment without any training, as a benchmark. The second manipulation involves communication. In some of our treatments participants are allowed to discuss strategies with their team members prior to the game so as to encourage team learning and coordination. While in other treatments where communication is not allowed, participants are required to reflect on their strategies individually.

Our results show that the bullwhip effect persists in the simulated supply chains with the stationary demand distribution and visible supply line. We also find that neither training nor communication by themselves eliminate the bullwhip effect. However, when communication is combined with system-wide training, supply chain performance improves markedly. This result indicates that the bullwhip effect is, at least in part, due to insufficient coordination between supply chain partners, and it also reveals the critical interaction between the two behavioral explanations advanced in the literature. It further implies that to be more successful practices or programs designed to improve supply chain performance should concurrently address both individual's decision biases and insufficient coordination among supply chain partners.

In the following sections, we present detailed experimental design and implementation (Section 2), build up optimality benchmarks (Section 3), report experimental results (Section 4), and discuss managerial implications and limitations of our study (Section 5).

2. Experimental design and implementation

We follow the basic protocol of the ''beer distribution game'' used in previous experimental studies. The game simulates a multi-echelon serial supply chain consisting of a *Retailer* (R), a *Wholesaler* (W), a *Distributor* (D) and a *Factory/Manufacturer* (M) with exogenous *Customer* demand. Assigned one of these roles, each participant manages her own inventory by placing orders to the upstream supplier for replenishment so as to satisfy demands downstream over multiple periods.

Each period begins with the arrival of shipments, which increases one's inventory. Next orders placed by the downstream customer are received, which are either filled when inventory is available or become backlogged. Each participant then makes an ordering decision and carries any remaining inventory/backlog over to the next period. The decision task is complicated by the existence of lead-times/delays in the supply chain: *order processing delays* (two periods) and *shipment delays* (two periods) *or production delays* (three periods and only for the manufacturer). See Croson and Donohue (2002) and Sterman (1989a) for further details of the game.

Our study was conducted using the computer interface. Fig. 1 displays the screen shot from the game as well as its initial conditions. In the actual experiment, each player could see her own current inventory and supply line, orders placed for past two periods, as well as the incoming shipments and orders (which is the customer order for retailers). History on one's own inventory level, orders received and placed was also available to subjects in graphs.

As in most previous work, we initialized orders and shipments in process to be 4 units, and starting inventory at each echelon of the chain to be 12 units. Each team was given an endowment of 5000 tokens, and all participants were told they would incur inventory cost of 0.5 token per unit per week and backorder cost of 1 token per unit per week. Final team earnings in tokens were the difference between the initial endowment and

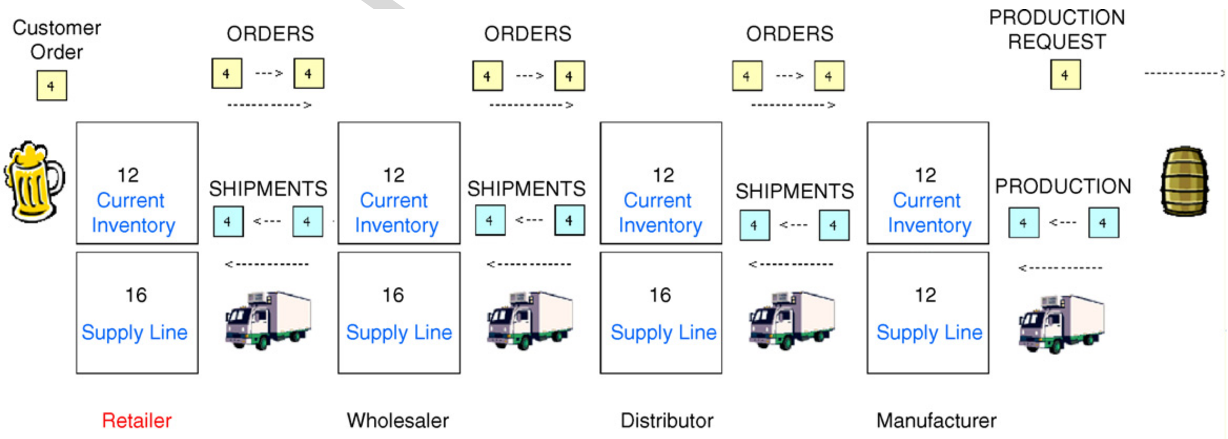

Fig. 1. Screen shot of the beer game and initial settings for all treatments. *Note:* In the actual game each player could see her own current inventory and supply line, last two orders placed, and the incoming shipments and orders (customer orders for retailers). Players could not see the above information of others.

the cumulative holding and backorder costs of all team members. At the end of the session the team earnings were converted to US dollars at a pre-determined exchange rate and split equally among the four team members. All experimental sessions last 48 periods/weeks, which is unknown to participants to avoid the end-of-game behavior.

As mentioned in the introduction, our design differs from prior work in several aspects. First, as in Croson and Donohue (2003, 2004), we control the customer demand distribution to be uniformly distributed from 0 to 8 units. Participants are told that the demand is between 0 and 8, with each integer in that range equally likely. The same demand stream is used in all treatments. Second, in our experiments participants see on the screen the number of units in their own *supply line*.

Lastly, we add a *training session* and a *study session* prior to the 48-period game. The training session consists of 20 periods. Participants either practise as teams to obtain role-specific experience, or train as central planners that make ordering decisions for all roles sequentially by walking between four computers placed in a row that represent the serial supply chain. Results from training session are shown to the participants, but do not affect their final earnings. The study session that followed lasts 10 min, and participants are encouraged to study the instructions of the experiment, finish a quiz, and think about strategies to be used in the actual game either independently, or through team meetings, depending on the treatment. This manipulation controls for the amount of time participants are allowed to reflect on the game, so that any difference can be attributed to the availability of communication.

In summary, we have a 3×2 design: the three types of training are none, role-specific, and system-wide, each conducted with and without communication. Table 1 summarizes our experimental design and sample sizes. Most of the six treatments involved eight teams of four participants, for the total of 192 participants. All sessions were conducted at the Laboratory for Economic Management and Auctions (LEMA) at Penn State, Smeal College of Business, between Fall 2003 and Fall 2004. Participants, mostly undergraduate business majors, were recruited using the on-line recruitment system, with cash the only incentive offered.

Table 1
Basic design (sample sizes in parentheses)

Communication availability	Training protocols		
	None	Role-specific	System-wide
No	NN (8)	RN (8)	SN (8)
Yes	NC (8)	RC (9)	SC (7)

The experiment proceeds as follows. Participants are randomly assigned to computer terminals that determine their roles and teams in the game, and study the instructions about the rules and settings of the game.[1] After we read instructions to them aloud and answer questions, the 20-period training session begins (except Treatment NN that does not include the practice game).[2] A 10-min study session then starts followed by the actual 48-period game. In the role-specific training treatments participants keep the same role as they had in the practice game, but teams are re-shuffled.[3] At the conclusion of the sessions subjects fill out a questionnaire before receiving their final payments. Average earnings of our experiments, including a $5 participation fee, were $22 and all sessions lasted approximately 90 min.

3. Theoretical benchmarks

Before we analyze the data to examine the effectiveness of our manipulations, we compute theoretical performance benchmarks in our settings.

Clark and Scarf (1960) study inventory models with stationary and known customer demands and lead times. They have shown that it is optimal for decision makers to follow an order-up-to policy, keeping inventory position (on-hand inventory plus outstanding orders, that we also call the supply line), at some constant levels to cover demands during lead times.

Applying the Clark and Scarf (1960) method to our context, we compute the optimal order-up-to levels to be 22 for R, W and D, and 18 for M. When the system is in equilibrium, following this policy requires each supply chain member to ‘‘pass through’’ his orders from his immediate customer to his immediate supplier. If all members were to follow this policy, the standard deviation of orders at each echelon would equal to the standard deviation of customer order, which is 2.74 (due

[1] All instruction materials for the experiment can be found at: http://lema.smeal.psu.edu/katok/learn_instructions.pdf.

[2] Role-specific training lasts on average 18 min, while the system-wide training lasts 21 min, which is a little bit longer since subjects have to physically move back and forth between computers to make four decisions in each period.

[3] Subjects are re-shuffled to avoid the situation where the same group of subjects plays together longer (i.e., both the training session and game session) than others.

to the uniform customer demand distribution we employed), and no amplification should exist after the supply chain reaches steady state. In a 48-period game that starts R, W and D with the inventory position of 24 and M with the inventory position of 21, the actual order standard deviation would be slightly higher, since supply chain members would have to slightly decrease their inventory positions initially to reach the desired inventory position.

Although deriving this decentralized optimal policy that minimizes local supply chain costs does not require any global information of the system, it is not intuitive and must be made under the assumption that all members are rational and trust each other to follow the same optimal policy. Indeed, we did not observe any precise ‘‘pass-through’’ behavior in any of our treatments.[4]

Chen (1999) constructs a team model in which the division managers share a common goal to optimize the supply chain performance with lead times and known stationary demand. We follow his analysis to set up a centralized ordering strategy.

Note that the holding and backlog costs are the same for each echelon in our supply chain setting. Following Chen's results, it would be unnecessary to hold any inventory at any echelons above the retailer as long as the retailer carries enough safety stock to cover the stochastic customer demand, and orders a constant amount that equals to the average customer demand (in other words, the retailer absorbs all variability in the system). For example, an extremely simple strategy in our setting would be for the retailer to keep his initial inventory position on 24, and for the other three team members to eliminate on-hand inventory by ordering 0 s for the appropriate number of periods[5] and to order 4 s subsequently. This strategy would cause the order variance to be zero for all supply chain members when the system reached steady state, but in a 48-period game variability of orders would increase from 0 for R to 0.98 for W to 1.34 for D to 1.58 for M.

This centralized ordering strategy is straightforward in a way that captures much of the initial status of the system (4 s in the pipeline). However, in order to discover it, a systems understanding of the supply chain is required; in order to implement it successfully, supply chain members have to coordinate their actions. Interestingly, in the treatment with both system-wide training experience and coordination opportunities provided, three (out of seven) teams exhibit behaviors approaching this potential. Since this strategy is clearly deliberate and reflects both, a good understanding of the system as well as coordination, this behavior is unlikely to have come about by chance.

4. Experimental results

We measure the supply chain behavior by comparing variability of orders (median standard deviation of orders placed) in different treatments.[6] Comparisons based on system cost yield very similar results and are more dependent on the specific cost structure in the experiment, and are thus not reported in this paper.

4.1. Supply line visibility

Cognitive learning theories define learning as a change in states of knowledge due to processing of information (Bower and Hilgard, 1981). Hence, improvement on individual's learning largely depends on how information is selected and transformed (Nonaka, 1994). On the other hand, theories of bounded rationality argue that humans have limited information-processing capacity, and for this reason, people tend to limit their mental effort while making decisions (Simon, 1979).

A methodological observation with prior experimental studies reveals that although underweighting the supply line has been recognized as a major cause of the bullwhip effect, this critical information is typically not readily available to decision makers. To be precise, participants have access to information on their own past orders and shipments received, however, extra mental effort is required to compute outstanding orders. Therefore, it remains possible that this challenge to subjects' limited computation capacities induces the tendency to ignore supply line information and hinders potential learning. If that is the case, then computing the supply line information will decrease the bullwhip effect, as our first hypothesis suggests.

[4] In Treatment SC, one team member mentioned this kind of strategy in the discussion, but was rejected by the other members.

[5] They are three periods for W, six periods for D and nine periods for M.

[6] We use the Grubbs procedure (see Grubbs, 1969) to test for outliers in the data we collected, which compares standard deviation of order placed for each individual to those of others in the same role/treatment category. An observation (a team) is eliminated if two or more members do not pass the Grubbs criteria. Only one team in our entire experiment was found to be an outlier and thereby we exclude this team from the main text of statistical analysis. Including the team does not change the basic results.

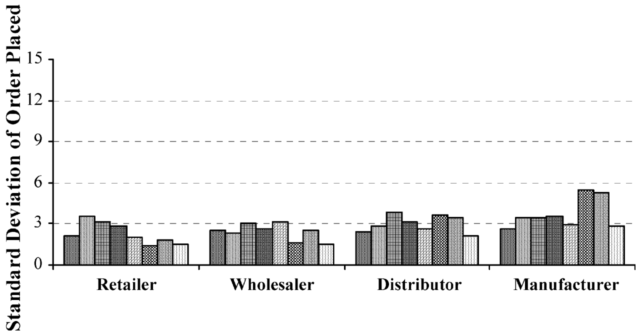

Fig. 2. Median standard deviation of orders placed in NN, by role and team.

Table 2
Basic statistics of median standard deviation of orders placed by role and treatment

	NN	RN	SN	NC	RC	SC
Retailer	2.072	2.221	2.133	2.162	1.744	1.561
Wholesaler	2.533	2.282	2.499	2.586	1.699	1.142
Distributor	2.967	4.133	2.852	2.397	2.695	1.271
Manufacturer	3.434	4.977	3.566	3.134	3.274	2.917
Overall median	3.026	3.721	2.766	2.556	2.300	1.745
Overall average	2.859	4.386	2.838	2.820	2.571	1.942
Overall S.D.	0.460	2.930	0.850	1.100	0.860	1.111

Hypothesis 1 (*Bounded rationality*). Visible supply line information will (a) remove order amplifications, and will (b) decrease order variations.

Fig. 2 displays standard deviations of orders placed, separated by team and role for Treatment NN, our baseline with direct information on supply line but without training or communication. The estimated median standard deviations of orders placed for each role are 2.07, 2.53, 2.97, and 3.43 for R, W, D and M, respectively. These median standard deviations for all treatments are summarized in Table 2. To statistically test H1, we use a non-parametric sign test (see Siegle, 1965, p. 68) to examine order amplifications. Summary of the sign tests for all treatments is reported in Table 3. If amplification exists, then the standard deviation of the *i*th echelon in the supply chain, σ_i, exceeds that of its immediate customer, σ_{i-1} (for all $i \in \{R, W, D, F\}$). If there were no amplifications, we would observe $\sigma_i > \sigma_{i-1}$ at the chance rate of 50%. Our data reveal that for 71% of the cases (17 out of 24), $\sigma_i > \sigma_{i-1}$, rejecting Hypothesis 1 at $p = 0.011$. Hence, order amplification remains even when supply line information is visible.

We did not conduct a treatment without displaying the supply line, so we cannot make a formal statement about what effect it has on order variability. When we compare the variability of orders in our Treatment NN with the baseline treatment of Croson and Donohue (2004), we find that the average standard deviation of orders is somewhat lower in our experiment than in theirs. However, since the two studies use a different subject pool and a different realization of customer orders, this comparison is merely suggestive rather than conclusive.

Making the supply line visible may slightly improve performance, but we do not know how subjects utilize this information to create *knowledge*, which is more than mere facts and bits of information but based on the understanding and the insights developed (Adler, 1986). Clearly, the knowledge created is not effective enough to eliminate the bullwhip effect, since order amplifications and much of the variation still remain in Treatment NN. Our post-game survey also indicated that many subjects did encounter difficulties in understanding the concept of outstanding orders.

4.2. Training

There is evidence that *experience* sometimes enhances learning (Schmidt et al., 1986; Taylor, 1975). Some even define learning as a change in behavior due to experience in a given situation (Bower and Hilgard, 1981). In this section, we further explore the effect of giving participants different hands-on experience on the

Table 3
Amplification comparisons by sign test

Treatment	Success rate (%)	Overall p-value	Sign test comparison at adjacent roles		
			Retailer vs. wholesaler	Wholesaler vs. distributor	Distributor vs. manufacturer
NN	70.8	0.011	0.363	0.035	0.004
RN	79.2	0.001	0.145	0.035	0.000
SN	83.3	0.000	0.004	0.004	0.035
NC	66.7	0.032	0.145	0.363	0.004
RC	66.7	0.076	0.254	0.020	0.090
SC	83.3	0.000	0.363	0.000	0.000

simulated supply chain performance. In the rest of the paper we explicitly refer to this experience as *training*. It is our view that looking at the effect of this simple type of training is a first step towards understanding the effect of training more generally.

Most formal corporate training programs are classroom-based, and involve trainer-led instruction and specific skill transfer. While this education-oriented training demands ex-ante knowledge, the fast changing competitive environment and technological developments mean that there are not always clear-cut rules for every decision task (Gordon, 1993). And in such situations, decision makers often rely on their ex-post experience to respond. Studies in the training literature advocate on-the-job training programs that promote experience-based learning to help managers develop "principles" for judgment (Bernard and Berney, 1983; Gordon, 1993; Morrison, 1989; Wehrenberg, 1987). In the area of operations management, giving people hands-on experience with information distortion through playing the beer distribution game is currently almost a required part of any MBA course in operations.

4.2.1. Role-specific training

The supply chain setting we investigate is inherently dynamic, unstable and sensitive to human errors. A team with one member behaving erratically has little chance of performing well, even if the other three members understand the system. An early "unintentional" error by one person could cause the entire supply chain to go out of control (see Croson et al., 2005). In most previous experimental studies involving the beer game, participants play the game one time.[7] This is a reasonable procedure because the studies investigate dynamics, and participants play one time in all treatments, so there is no a priori reason to think that repeating the game (without any further intervention) should improve performance, or account for a treatment effect. In our case, however, repeating the game is necessary because the type of training is one of our treatment variables. Additionally, this design provides a way to measure the extent to which the bullwhip behavior reported in the literature might be due to participants' misunderstanding of the game.[8]

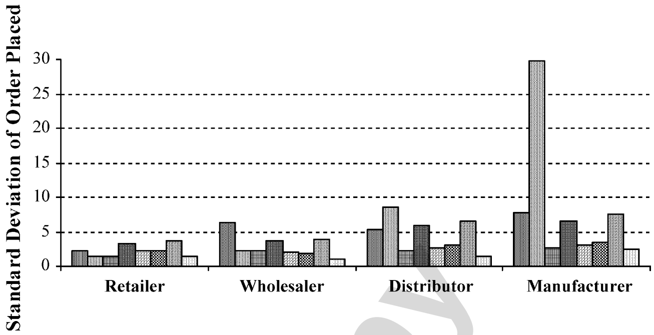

Fig. 3. Median standard deviation of orders placed in RN, by role and team.

In Treatment RN, participants play in a 20-period training session before the actual game. After this extra role-specific experience is obtained, subjects are given 10 min to individually reflect on their experience, work out a quiz that tests their knowledge, and think about ordering strategies. If the bullwhip behavior is induced by unsystematic human errors, and if any effective experiential learning occurs given the hands-on training, we would expect that repeating the game will decrease order variations and amplifications in Treatment RN relative to Treatment NN as formally tested by the below hypothesis.

Hypothesis 2 (*Experiential learning*)**.** If the game is repeated (a) order amplifications and (b) order fluctuations will decrease.

Fig. 3 displays standard deviations of orders in Treatment RN. Both order oscillations and amplifications clearly remain. The sign test suggests that order amplifications are highly significant: $\sigma_i > \sigma_{i-1}$ in 79% cases (19 out of 24) which is different from the 50% chance rate at $p < 0.001$. The median standard deviation of orders is 3.72, which is not statistically different from that in Treatment NN by the Wilcoxon test (one-sided $p = 0.323$), so we reject both parts of H2. See Table 4 for the summary of the comparison between all pairs of treatments using the Wilcoxon test.

Table 4
Oscillation comparisons by Wilcoxon test

Treatment	RN	SN	NC	RC	SC
NN	0.323	0.439	0.191	0.240	*0.036*
RN		0.221	0.164	**0.084**	*0.014*
SN			0.253	0.212	*0.047*
NC				0.245	**0.060**
RC					*0.071*

Note: One-sided *p*-value is reported with strongly significant differences highlighted in italic, and weakly significant in bold.

[7] Croson et al. (2005) report on a treatment in which participants play the game with constant and known customer demand two times, each time in the same role but as part of a different team. They report that repeating the game decreases order variability but far from eliminates the bullwhip effect.

[8] Some participants in Treatment NN expressed confusions with understanding the game in the post-game survey, which they believe affected their performance.

So far we have demonstrated the persistence of the bullwhip behavior in a highly controlled laboratory environment. Repeating the game, by itself, does not improve performance, so the bullwhip effect in the laboratory is unlikely to be caused by unsystematic human errors. Providing decision makers with role-specific hands-on experience may induce individual learning, but it is not sufficient enough to enhance the overall supply chain performance. This experimental evidence is consistent with the observation that even highly experienced supply chain managers cannot avoid the bullwhip effect in practice.

The lack of direct feedbacks and "system knowledge" may account for the failure of our role-specific training. Learning theories state that people learn most effectively when they are able to observe direct feedback on their decisions (Hogarth, 1980). Yet in a supply chain system feedback is delayed due to the existence of lead times and further complicated by the behaviors of other decision makers. In some early beer game experiments, Sterman (1989a) finds that subjects often attribute the origins of the supply chain dynamics to the unpredictability of customer orders, and he notes that "... learning from experience may be hindered by such misperception (Sterman, 1989a, p. 336) ...". Similarly, as revealed by the post-game comments, most participants in our study related their poor performance to the erratic orders (including customer orders) they received that directly change their current inventory levels, yet few noticed that it is also a result of not taking a full account of the supply line in placing their own orders. In other words, subjects lose connection between their actions and the feedback they received in managing the system.

Moreover, practising only in specific roles may prevent participants from observing the interrelationship with other decision makers in the supply chain, and the long-term consequence of their own decisions thereafter (March and Olsen, 1975; Senge, 1990). For example, subjects in our experiments often failed to realize that unusually high orders they placed would likely knock their suppliers out of stocks, which will in turn make their own lead times unpredictable. The fact that system performance depends so heavily on the decisions of each individual member makes the beer game difficult to understand and manage. We thus conjecture that the inability to see the system as a whole may be another reason for the poor performance, which leads us to our next treatment.

4.2.2. System-wide training

In Treatment SN participants play as the central planners in the 20-period practice game, placing orders for all members of a supply chain. The benefits of system-wide training have been acknowledged by practitioners and academic researchers. Managers in large corporations are often sent to work in different departments so as to better understand the system structure and interrelationship of the overall organization. Similarly, the research work by Senge and Sterman (1992) advocates that tools involving "learning laboratories" or "microworlds" where managers play roles in simulated organizations to experience the long-term, system-wide, dynamic consequences of decisions, will accelerate learning. A recent work by Hwang (2003) also argues that systems thinking should be incorporated into the design of training strategies.

We apply the idea of "systems learning" to the beer game context, and expect system-wide training to improve behavior by providing more direct feedbacks without other agents' interference (although time lags remain) and promoting mutual understanding of the system interrelationship, as states formally the following hypothesis.

Hypothesis 3 (*Systems learning*)**.** System-wide training will (a) remove order amplifications, and (b) decrease order variations.

Fig. 4 depicts standard deviations of orders in Treatment SN. Contrary to H3a, orders amplifications persist, $\sigma_i > \sigma_{i-1}$ in 83% cases (20 out of 24), and $p = 0.0001$. More surprisingly, contrary to H3b, the median standard deviation of 2.77 in Treatment SN is not significantly different from that in Treatment NN or RN ($p = 0.439$, 0.221, respectively).

A review of some of the research on organizational learning sheds lights on why system-wide training *by itself* did not prove to be successful. Organizations can be best described as systems of interrelated roles (Simon, 1991), and so do supply chains. As mentioned in the introduction, the performance of an organization not only depends on how well individual decision

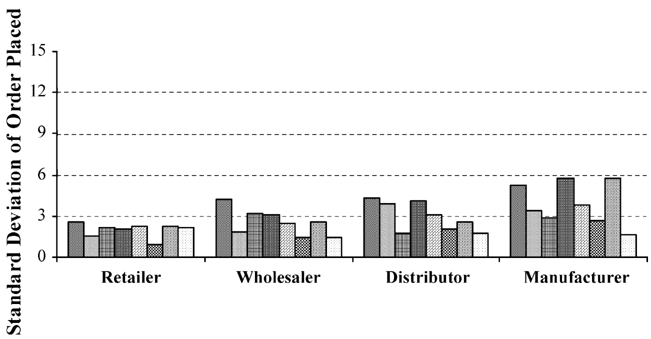

Fig. 4. Median standard deviation of orders placed in SN, by role and team.

makers within it learn, but also or even more importantly, how well knowledge thus created is transformed to shared perspectives and coordinated actions of the organization. And it is the *communication processes* that serve as a bridge between individual and organizational levels of learning (Cohen and Levinhal, 1990; Huber and Daft, 1987; Rahim, 1995; West and Meyer, 1997).

This observation about the critical role of communication is in line with findings of Croson et al. (2005), that coordination risk triggers instability in supply chains.[9] Our post-game surveys are also suggestive of this view: many subjects recognized the importance of smoothing order flow in the supply chain after system-wide training, yet they had to deviate from their original strategies in response to unanticipated teammates' misbehaviors (e.g., big orders from downstream or no shipments from upstream),[10] and regrets of not being able to convey ideas to team members were reported too.[11]

Previous discussion suggests that system-wide training (or training in general) does improve understandings for many individuals; however, since it is not equally effective for all individuals, and since communication is prohibited in the experiments, insights and knowledge gained cannot be effectively translated into ordering strategies or improved system performance. This leads us to the next set of treatments that involve communication.

4.3. Communication and its Interactions with training

Cooperative learning, an approach that encourages group members to collaborate on a collective task through face-to-face communication, has been demonstrated to successfully enhance learning in both education (Springer et al., 1999) and training literatures (Doyle, 1991; Schendel, 1994), and in the following treatments we investigate its effect on the behavior in our simulated supply chains.

Treatments NC, RC and SC differ from their counterpart Treatment NN, RN and SN only in terms of the availability of communication. During the 10-min team discussion (after training if any) prior to the 48-period game, group members are encouraged to study experimental materials, share training experience, and develop team strategies collectively.[12]

We expect communication to improve performance for two reasons. First, communication allows participants to exchange insights obtained from training, so that at the end of the discussion all team members may have a similar level of understanding of the system. For instance, if any teammate recognizes the importance of supply line information on making ordering decisions, being able to share this idea with other members should help alleviate the overall tendency to underweight unfilled orders. Second, communication may help develop an explicit team strategy that can be used to decrease the uncertainty about the actions of other teammates, reducing the coordination risk. This leads to our final hypothesis.

Hypothesis 4 (*Organizational learning***).** Communication, (a) when combined with training, will improve performance (in terms of the decrease in order oscillations and amplifications), but communication (b) without training will have no effect on performance.

Figs. 5–7 reflect data in Treatment NC, RC and SC. Team 8 in Treatment SC is detected as an outlier by the Grubbs procedure, and is therefore excluded from subsequent analysis. The basic statistics for these treatments and others, treatment comparisons by Wilcoxon test and Sign test are summarized in Tables 2–4 accordingly. To test H4, we compare the variability of orders in Treatment NN and NC (the two treatments without training). The Wilcoxon test shows no significant decrease in variability (one-sided $p = 0.191$), indicating that, consistent with our hypothesis H4b, communication alone fails to alleviate the bullwhip effect. Next we compare RN with RC, as well as SN with SC, to examine the communication effect *after* training. Results show that communication after

[9] There is a slight difference in the two interpretations. Croson et al. (2005) argue that a pre-perceived coordination risk induces bullwhip, while our finding suggests that most people start with their "optimal" strategies trusting the others to follow the same, then panic and deviations occur when unexpected behavior is encountered.

[10] Ten subjects (out of 32) in Treatment SN clearly claimed in the post-survey that their strategies were to order consistently with small variance, for example, as one Wholesaler wrote: "I tried to the keep the orders within 1 higher or lower of the previous order to allow my immediate supplier to predict my orders... To fix backlog only try to iron out the problem slowly, instead of making one big order that will mess up the rest of the chain". Another two subjects claimed that they were using the pass-on-order strategy until they were hit by big order swings.

[11] In answering what else information will help with their performance, 12 subjects (out of 32) called for some forms of communication in the survey.

[12] Discussions of most teams in our study were recorded, with participants' permission.

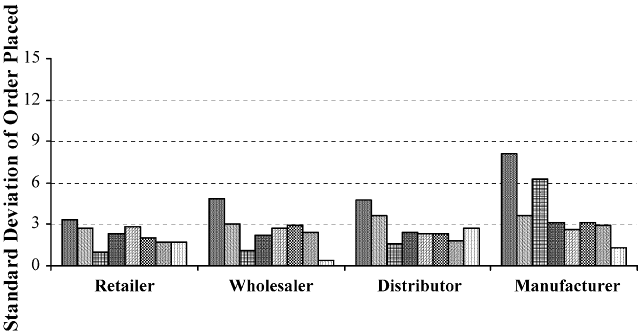

Fig. 5. Median standard deviation of orders placed in NC, by role and team.

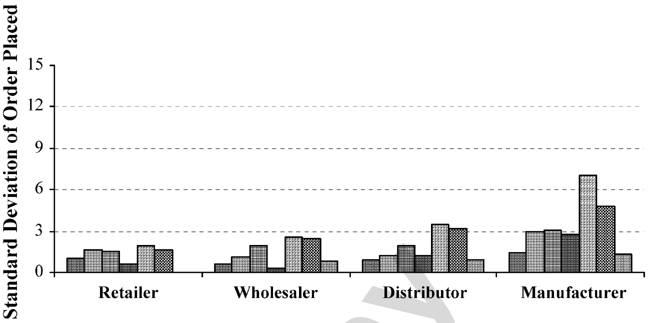

Fig. 7. Median standard deviation of orders placed in SC, by role and team.

both types of training helps reduce order variability (weakly so for role-specific training, one-sided $p = 0.084$, and more significantly so for the system-wide training, one-sided $p = 0.047$). Overall, our data is consistent with H4.

Our main conclusion is that the effectiveness of communication in reducing the bullwhip effect relies on the training protocols that participants follow. Communication without training fails to correct misbehaviors. Training by itself, does not improve performance. However, combining training and communication together alleviate the bullwhip effect. Thus, we conclude it is the *interaction* between training and communication that is important. Training contributes to the accumulation of critical knowledge for the participants that leads to more effective discussions and team strategies, whereas communication serves to transfer ideas or insights gained by individuals to shared understanding and coordinated behavior of the supply chain as an organization. Both components must be present to improve performance.

Answers in the post-game survey are also indicative of the interaction effect. In the questionnaire we asked participants to rate, on a scale from 1 to 7, the usefulness of the training session, and of the communication opportunity.[13] Overall, training was perceived as useful (average rating of 6.1 on a 7-point scale) and the perceived usefulness of training was not affected by the presence of communication. However, the perceived usefulness of communication was significantly affected by the presence of training. The average rating in the NC treatment was 4.85, and this increased to 6.57 and 5.88 in the RC and SC treatments, respectively (the differences between RC and SC are not statistically significant, with the two-sided *t*-test *p*-value of 0.394). The differences between NC and the two treatments with training are statistically significant in both cases (two-sided *t*-test *p*-value is 0.001 for the NC versus RC comparison and 0.032 for the NC versus SC comparison). This result provides an additional manipulation check that confirms the interactive relationship between training and communication: not only does the variability of orders decrease, but also the perceived usefulness of communication increases when communication follows a training session.

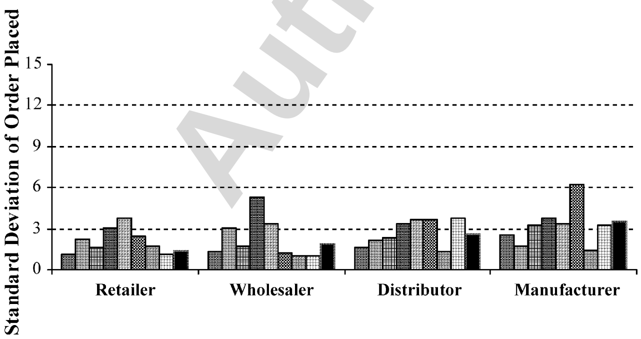

Fig. 6. Median standard deviation of orders placed in RC, by role and team.

Our data is also suggestive of the fact that system-wide training might be more effective than role-specific training when communication is available (although both of them are clearly more effective than no training at all). To formally establish the result, we compare order variability in Treatment SC with that in NC and RC, and find slight improvement in both cases (one-sided $p = 0.06$, and 0.071, respectively).

5. Discussion and conclusion

We report on a study that examines the effect of training and communication on decision-making

[13] These questions were asked only in treatments in which they were relevant—the training question was asked in treatments with training and the communication question in treatments with communication.

process in a dynamic supply chain simulation. We find that the bullwhip behavior observed in prior studies is quite robust. Directly displaying the supply line information does not eliminate the bullwhip effect. Allowing participants to have extra hands-on experience does not improve performance, and neither does allowing teams to communicate without prior training. However, *when training is combined with the opportunity to share knowledge and coordinate through communication, performance improves with reduced order oscillations*. This result indicates that the observed supply chain instability is, at least in part, due to insufficient coordination between supply chain partners. It also reveals that training may serve to build up individuals' knowledge and thereby enhance their decision quality, while communication may serve to successfully transfer individual learning into coordinated organizational actions that eventually lead to better system performance. There is a critical interaction between the two behavioral explanations advanced in the literature.

Our data indicates that when participants are able to communicate, system-wide training appears to be somewhat more effective than role-specific training, when the effectiveness is measured as the decrease in order variability. This result might have potential bearing on the types of training and communication that goes on within organizations and supply chains. Successful programs designed to improve supply chain efficiency should address both individual decision biases and insufficient coordination among multiple agents simultaneously.

Future research in this area may examine the robustness of our results on training and communication in different supply chain settings, for example, under different demand distributions. One potential limitation of our study is that what we call training is really hands-on experience. This type of training is a reasonable first step, but other types of training are worth investigation, such as educating participants about the bullwhip effect and the optimal ordering policies. More work could also be done to explore the impact of other practices besides communication that facilitate coordination (e.g., collaborative planning, forecast and replenishment—CPFR) on alleviating the bullwhip effect. Finally, additional empirical work is clearly needed to test the applicability and accuracy of our experimental results.

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