The final reference for this work is as follows:


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Testing the Potential of RFID to Increase Supply-Chain Agility and to Mitigate the Bullwhip Effect

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ABSTRACT

This study examines the potential of RFID technology to increase the agility of supply-chain e-commerce systems by mitigating the bullwhip effect. The bullwhip effect is a supply-chain phenomenon that reveals a lack of business agility characterized by the amplification of inventory variance. This study employs an experiment involving a modified Beer Distribution Game to simulate an RFID-enabled supply chain. The results provide empirical evidence that RFID technology can increase a supply chain’s agility and reduce the bullwhip effect by reducing inventory holding costs, stockout costs, and inventory-level variances. The results are all the more important when applied to interorganizational e-commerce systems.

KEYWORDS: RFID, supply-chain agility, bullwhip effect, beer distribution game, e-commerce, interorganizational systems, information systems
INTRODUCTION

Given the volatile nature of markets and increasingly dynamic performance requirements of business, agility is one of the challenges to international business (Van Hoek, Harrison, & Christopher, 2001). Agility is a vital characteristic that companies need in order to sustain their competitive advantage in the new order of world business (Sharifi & Zhang, 2001). This is especially true with the more complex, rapid, and integrated nature of e-commerce, where solving supply-chain issues is paramount, such as with interorganizational systems where companies share information about their supply chains and other data (Chi, Holsapple, & Srinivasan, 2007; Hsu, Kraemer, & Dunkle, 2006). Finding ways to proactively manage the supply-chain electronically and to reduce uncertainty has long been a key goal of e-commerce (Bodendorf & Zimmermann, 2005; Ho, Chi, & Tai, 2005). We posit that RFID is a key technology that will help with this proactive management.

RFID technology has received much attention in recent years as major manufacturers such as Wal-Mart, Gillette, Target, the U.S. Department of Defense, Albertsons, Best Buy, and hundreds of others have committed themselves to incorporating this technology into their supply-chain information systems in an effort to increase the agility of these systems and gain a competitive advantage (Kinsella, 2003, 2005). Agility leading to competitive advantage is particularly critical with e-commerce, where pressure on trading partners can be enormous with interorganizational systems (Hsu, et al., 2006). For example, as of January 2005, Wal-Mart has required its top 100 suppliers to utilize RFID technology at the pallet level for products entering its distribution system. Experts have estimated that Wal-Mart could save $8.4 billion a year when its RFID system is fully implemented (Roberti, 2003). These savings include $6.7 billion in reduced labor costs, $600 million in out-of-stock supply-chain cost reduction, $575 million in theft reduction, $300 million in improved tracking through warehousing and distribution centers,
and $180 million in reduced inventory holding and carrying costs (Asif & Mandviwalla, 2005). Leading UK retailer Marks & Spencer field-tested RFID by tagging 3.5 million storage bins. Formerly it took approximately 17.4 minutes to scan 25 trays with barcodes. With RFID tags, 36 pallets were read in 3 minutes (Wilding & Delgado, 2004).

Because Radio Frequency Identification (RFID) is a technology with the potential to increase the agility of traditional supply chains and interorganizational supply chains, RFID has strategic and global implications for e-commerce. Because of its range of applications and its increasing adoption, RFID technology is a potentially strategically disruptive technology that can change many information management and supply-chain practices. Proponents claim that RFID technology can potentially enable supply-chain managers to overcome problems caused by imperfect or insufficient information inherent in current inventory management systems (e.g., Asif & Mandviwalla, 2005). One way strategic advantage can occur with RFID is that RFID “increases the feasibility of implementing alliances of firms that exchange information to coordinate production and distribution, outsource functions and services, and partner with suppliers and intermediaries” (Straub, Rai, & Klein, 2004).

Of particular interest to this study is the concept that RFID technology can potentially increase the business agility of inventory supply chains by mitigating what is known in supply-chain management circles as the bullwhip effect (Asif & Mandviwalla, 2005; Lee, Padmanabhan, & Whang, 1997b). The bullwhip effect is a supply-chain phenomenon in which suboptimal inventory order levels occur due to the amplification of imperfect information as it is transmitted through the supply chain (Lee, et al., 1997b). Amplified order variance caused by distorted information, in turn, results in alternating inventory stockouts and surpluses that cause large cost inefficiencies (Steckel, Gupta, & Banerji, 2004). This phenomenon directly relates to business agility in using information systems to increase supply-chain coordination (Bowersox,
RFID tags provide each tier of a supply chain with accurate, real-time information about inventory levels along the supply chain. This information can increase supply chain agility and decrease the bullwhip effect by helping prevent information distortion. Although the technical merits of RFID tags are well documented, because RFID technology is still emerging, there is little available information that examines the extent of RFID technology’s capability to mitigate the bullwhip effect.

The wireless technology involved with RFID is proven and can be mass produced. However, what is not fully known or proven are the effects that RFID can have on information in a supply chain. The object of this study is to examine the effect that can result from the bi-directional flow of supply-chain information using RFID. Accordingly, this study presents hypotheses and an experiment in an effort to link previous research on the bullwhip effect to the potential of RFID supply-chain information systems, thereby increasing supply-chain agility and reducing the bullwhip effect. The experiment involves a modified Beer Distribution Game (BDG) (Sterman, 1989) to simulate an inventory supply-chain system that is enabled with RFID technology. A fundamental difference between the employed simulation and the traditional BDG is that in the employed simulation, each supply chain tier has full visibility of the rest of the supply chain—both upstream and downstream—in order to accurately mirror a key enabling capability of RFID (Lee & Ozer, 2007). Such visibility has been shown to be critical in successful e-commerce supply chains (Yang, Mason, & Chaudhury, 2001).

The absence of the wireless mechanics of RFID does not inherently lessen the simulation’s ability to explore the potential informational impact of RFID. Enhanced information available through RFID is the object of this study, not the RFID apparatuses themselves or their underlying technical performance characteristics, which are well proven and documented.
Glidden et al. (2004) further support the scope and aim of our study by stating:

> It is actually not the tag or reader that is the significant development, but rather the information itself—about the location and status of goods worldwide, to manufacturers, distributors, and retailers simultaneously—that makes RFID an enabling technology (p. 140).

This study intends to reveal the impact of information made available through RFID technology within a vertical supply-chain system. In so doing, this paper will help develop an understanding of cause and effect principles related to RFID technology that can be further added to, refined, and expanded in future e-commerce research.

The remainder of the paper builds a theoretical model based on the bullwhip effect and supply-chain agility. Hypotheses are operationalized to test our model of the effects of RFID on the bullwhip effect and supply-chain agility. Next, we summarize our laboratory experiment along with its results. Finally, we discuss the findings, contributions, limitations, and future research areas related to this study.

**THEORY AND HYPOTHESES**

**Bullwhip Effect**

Collectively, recent studies agree that the sharing of point-of-sale (POS) data throughout the supply chain can be useful in lessening the *bullwhip effect*. The term *bullwhip effect* was coined by managers at Procter and Gamble who noticed an amplification of information distortion as order information traveled up the supply chain (Lee, et al., 1997b). In one simulation, the bullwhip effect was attenuated by nearly 50% at the factory level by sharing POS information (Chatfield, Kim, Harrison, & Hayya, 2004). Chen et al. (2000) found, using a logistics formula, that supply chains that shared POS information would experience an additive increase in order variance, while supply chains that did not share POS information would experience a multiplicative increase in order variance. Despite the benefits of shared POS
information, several researchers have found that sharing POS information alone cannot eliminate the bullwhip effect, due to either complex demand patterns (Steckel, et al., 2004) or lead times and order-up-to policies (Chen, et al., 2000). In other words, POS data does not fully represent the supply chain. The solution is to improve the accuracy of information across the supply chain, and RFID may be a key technology in doing so. Figure 1 provides a high-level overview of the product and information flows in the beer-distribution game (BDG). Figure 2 then provides an enhanced illustration of the complexity of the product and information flows that naturally lend themselves to the bullwhip effect.

*Figure 1. Illustration of Beer Distribution Game Information and Product Flows*
Supply-chain Agility

Agility has been defined as the capability to operate profitably in a competitive environment of continually and unpredictably changing customer requirements and expectations (Goldman, Nagel, & Preiss, 1995). To achieve supply-chain agility and to avoid the bullwhip effect, it is critical that firms achieve visibility across their supply chains. This increased visibility can be accomplished by sharing information among supply-chain members through interorganizational information systems (Chi, et al., 2007; Hsu, et al., 2006). Indeed, the availability of information across tiers facilitated by information systems may significantly improve the performance of entire supply chains by reducing inventory levels, cycle times, and upstream demand variation (Olhager, 2002; Yang, et al., 2001).

Achieving the visibility necessary to foster supply-chain agility requires sophisticated information systems in organizations that participate in a supply chain (Goldman, et al., 1995). Gunneson (1997) highlighted that information technology is crucial and that high-level information systems are required for the agile enterprise. Other researchers, including Song and
Nagi (1997), believe that agile manufacturing makes use of modern information technology to form virtual enterprises, which enables them to respond quickly to changing market demands. Use of RFID is part of the overall information systems solution to increasing agility in supply chains.

**Visibility and the Bullwhip Effect**

Strategic, real-time collaboration within a supply chain is increasingly viewed as essential to gaining a competitive advantage. Conversely, two main factors contributing to supply-chain inefficiency and the bullwhip effect are the lack of collaboration and supply-chain visibility (Srivastava, 2004). Firms that do not strategically manage their supply chains and thus experience the bullwhip effect can incur tremendous losses. For example, Cisco Systems experienced the bullwhip effect in the spring of 2001, resulting in a $2.25 billion inventory write-off (Srivastava, 2004). In 1999 and early 2000, they had a critical shortage of networking components and thus could not meet customer demand; unfortunately, their flawed systems and procedures distorted demand signals, and they ended up with a parts inventory that dramatically increased—more than 300%—between the third and fourth quarters of 2000. Recognizing their strategic blunder, Cisco has since improved its inventory inefficiencies through a CPFR (collaborative planning, forecasting, and replenishment) system, of which RFID is an integral part. The Cisco case is just one illustration of the fact that “visibility can help identify the sources of variability and gradually lead to its reduction, resulting in much more efficient inventories” (Srivastava, 2004). As another example, in 2003, Roland Berger Strategy Consultants estimated that reducing finished-goods inventory in the consumer-packaged goods industry could reduce inventory by an average of $7 million for each manufacturer (Srivastava, 2004).

Similarly, we propose that this visibility can be greatly increased by RFID because RFID allows for Automatic Data Acquisition (ADA)—automated counting, synchronization, collaboration, sharing, and tracking across the supply chain. ADA is crucial to providing enough
information to lessen the bullwhip effect; without ADA, supply chains would not have the resources to capture sufficient information (Asif & Mandviwalla, 2005). Because of these factors, we believe that RFID can mitigate the bullwhip effect to a greater extent than attempting to mitigate the bullwhip effect by providing only POS data.

Given the literature and the initial evidence, it appears that proper use of RFID within a supply chain should increase supply-chain agility. However, the fundamental assumption of this proposition is that the RFID technology is supported by a sophisticated information system that is used across the supply chain. Accordingly, we propose that supply-chain systems with additional information resulting from usage of RFID technologies should have lower average inventory stockout costs as well as lower average inventory holding costs than those systems using traditional barcodes and limited inventory information.

Further, RFID-enabled supply-chain systems should not experience the amplification of order information distortion that is typical of the bullwhip effect (Lee, Padmanabhan, & Whang, 1997a). Higher tier supply-chain members such as wholesalers and manufacturers should have roughly equal levels of inventory holding and stockout costs. A more equal variance in inventory stockout and holding costs among supply-chain tiers should be reflected by a lower standard deviation of supply-chain holding and stockout costs than the standard deviation of supply-chain systems without RFID technologies. These claims are supported in related research by Chen et al. (2000), who provide an elegant series of theorems to show that, because of the bullwhip effect, there will be more variation in a simple POS supply chain than in a simple POS supply chain that is centralized. Like centralized POS data, RFID facilitates the centralization of data in a supply chain—providing transparency through instantaneous and global supply-chain information (Kinsella, 2003), (Sarma, Brock, & Ashton, 2000)—which should similarly lead to mitigation of the bullwhip effect and decreased variation.
Because imperfect information is so central to the occurrence of the bullwhip effect, this paper proposes that additional information available through use of RFID technology will enable inventory managers to regulate inventory stock within an appropriate range by setting “the inflow rate so as to compensate for losses and usage and to counteract disturbances which push the stock away from its desired value” (Sterman, 1989, p. 322). To operationalize the construct of appropriate inventory regulation, this paper uses two measures: (1) The cost of unnecessary inventory holding costs, which is determined as the holding cost of all inventory units that are not sold during a given sales period (Sterman, 1989); and (2) stockout costs.

We define the cost of foregone revenue or stockout costs as “the cost for having a backlog of unfilled orders” (Sterman, 1989, p. 326). These costs can come from many sources. If an item is not available for purchase, customers can react in one of four ways. First, they will wait for the product to become available. The selling company incurs no immediate financial cost from this reaction. Second, the company can backorder the item. Backorders cause the selling company additional costs associated with procuring, expediting, and delivering items that are no longer associated with the original order. Third, customers can purchase the item from a competitor. In this case, the company forgoes the revenue that might have been generated through the sale of the item, had the item been available. Fourth, in addition to buying the item elsewhere, the customer can choose to make all future purchases from the competitor. This reaction results in not only a loss of the revenue associated with the one-time purchase but also in the loss of the revenues associated with all future sales, which can be a substantial amount of money. Stockout costs are determined by the overall impact of these various customer reactions (Coyle, Bardi, & Langley, 2002). Not surprisingly, decreased holding and stockout costs have been illustrated as key potential benefits of the use of RFID (Asif & Mandviwalla, 2005). These two measures help operationalize the appropriate regulation of inventory because in order
to minimize stockout and holding costs, a firm must keep inventory levels within the optimum range. The use of costs to measure the bullwhip effect is a common approach, usually based on profit maximization or inventory cost minimization (Steckel, et al., 2004; Warburton, 2004). Agile supply chains are better able to match inventory levels with customer demand levels. Given these modes of operation, we propose that the use of RFID chips will enable supply chains to better regulate inventory levels within the optimum (most cost-efficient) range. The more efficient a supply chain is, the less the combined cost of holding and stockout costs will be. Conversely, the less efficient an inventory supply chain is, the higher the holding and stockout costs will be. Overall, use of RFID over time should lead to less total inventory on hand, lower total inventory costs, and smaller deviations in inventory on hand and in inventory costs.

Summarizing this section, we predict the following:

**H1**: RFID systems will have lower inventory levels across supply-chain tiers over time than traditional supply-chain systems.

**H2**: RFID systems will have lower total inventory costs across supply-chain tiers over time than traditional supply-chain systems.

**H3**: RFID systems will have lower variations in inventory levels across supply-chain tiers over time than traditional supply-chain systems.

**H4**: RFID systems will have lower variations in inventory costs across supply-chain tiers over time than traditional supply-chain systems.

**RESEARCH METHOD**

**Experimental Task**

To test the hypotheses, this study employed the BDG, a popular simulation in supply-chain circles used to demonstrate how poor information and low coordination of supply-chain members causes the bullwhip effect to occur. The BDG was developed at MIT to simulate the
bullwhip effect and has been used all over the world for many years (Munson, Hu, & Rosenblatt, 2003; Sterman, 1989). In a 1989 study, Sterman used the BDG to show how inventory decisions based on incomplete data can lead to wide fluctuations in the supply chain. According to Sterman (1989), the BDG is a “simulated inventory distribution system which contains multiple actors, feedbacks, nonlinearities, and time delays. The interaction of individual decisions with the structure of the simulated firm produces aggregate dynamics which systematically diverge from optimal behavior” (p. 321).

One of the advantages of using the BDG as a model is its use of a four-tier supply chain. Previous bullwhip effect studies have typically relied on a two-tier model, using a combined customer-retailer as the first stage and retailer-manufacturer as the second. Because this study involves the effect of providing full supply-chain visibility, a larger, four-tier model was chosen to better show the power of bidirectional visibility. In short, the BDG repeatedly demonstrates how the bullwhip effect can result from imperfect information.

We chose a computerized version of the BDG to improve the accuracy of our data capture and to better simulate the improved visibility that occurs through automation. Several other studies have successfully used a computerized version of the BDG. Steckel et al. (2004) used a simulated BDG to show the effects of sharing POS information. Hieber and Hartel (2003) used a similar simulation to test various supply chains for comparison of effectiveness. Croson and Donahue (2005, 2006) used a simulated BDG to show the effectiveness of information sharing within the supply chain.

**Experimental Design**

This experiment employed a one-way, post-test only, randomized experiment. Participants were randomly assigned to either the control or treatment conditions and then randomly assigned to teams of four within the control and treatment conditions. The treatment for the experimental group involved the simulation of an RFID-enabled supply chain. This RFID
simulation allowed participants to have full visibility into inventory levels and orders placed within the multiple tiers of the supply chain, while the control group participants were provided information relating only to their immediate tier.

This design is similar to those of Croson and Donahue (2005, 2006), who also used information sharing to mitigate the bullwhip effect. In (Croson & Donohue, 2005), full visibility of the BDG supply chain were provided to tiers for either upstream or downstream members but not for both simultaneously. Similarly, in (Croson & Donohue, 2006), full visibility was given to supply-chain tiers for both upstream and downstream members. However, information about inventory in transit between tiers was not provided, substantially reducing the realism of the simulated model. A key benefit of RFID technology is its capability of tracking inventory movements in transit along the supply chain (Lee & Ozer, 2007). Without this information, the effectiveness of RFID is reduced to that of barcodes, which can also be scanned at supply chain tiers. To more closely simulate the capabilities of RFID, this design provided full visibility to both upstream and downstream supply-chain members and provided information about inventory en route between tiers, providing a more accurate simulation of RFID technology.

Participants

The sample for this study was composed of 138 undergraduate students drawn from two large introductory, sophomore-level courses—one in accounting, the other in information systems—at a large university in the western United States. Ten participants were dropped from the study because of incorrect group sizes due to no-shows or technical issues with the software. This left a total of 128 participants (30% of the sophomores were female and 70% were male). Because both experimental and control group versions of the BDG were played using networked computers, it was not necessary for participants to know who their teammates were. Altogether, the participants composed 30 teams of four—15 teams each for both the control and the experimental groups. Small teams of four were chosen to conform to Sterman’s (1989) design
and because a large body of research has shown that for most tasks, groups with more than five
to six members start to perform suboptimally (Hackman & Vidmar, 1970; Hare, 1952; Slater,
1958). This size also fit nicely with our need to have each group member act as a manager of one
of the four tiers in the simplified supply chain.

**Research Tool**

The research tool used for the experiment was a custom-developed network program
based on the open-source group-interaction software, GroupMind. The software tool was used to
simulate a supply chain and to coordinate the inventory order decisions of participants within
teams of four. GroupMind uses dynamic HTML to collect, coordinate, and display the ordering
decisions of participants via a Web browser. Figure 3 shows a control group participant in the
role of the retailer. Per the traditional beer game, only local tier data is provided. This
information includes items such as how much inventory is on hand, how much the consumer has
demanded, and a total of inventory costs incurred so far by the retailer. The round or “week”
number is shown at the top of the screenshot as well as in a text field at the bottom of the
screenshot, where the participant can place an order once per round.
Figure 3. Screenshot of Control Group Simulation

Figure 4 shows a treatment group participant in the role of wholesaler. Consistent with RFID literature reviewed above, the treatment group simulation shows inventory and order levels for the entire supply chain as well as customer demand in the form of point-of-sale data. This information is displayed in a table in the center of the screenshot, providing full supply-chain transparency to the treatment group participant. Above the center table, the inventory level and costs for the current round are displayed, just as in the control group. However, to the right of this information is a simple inventory forecast that summarizes the inventory and order information presented in the center table. Below the center table, inventory costs are tallied for the wholesaler as well as for the supply chain as a whole.
Figure 4. Screenshot of Treatment Group Simulation

Procedures

Because traditional group interactions and processes can have severe behavioral process losses that could interfere with the experiment’s results—such as evaluation apprehension, social loafing, and production blocking (Steiner, 1972)—group members were not allowed to fully interact and communicate with other participants in or outside their assigned team. Further, because teams were randomized and participants interacted via a network software application, participants did not know who their other teammates were. This allowed participants to place orders in anonymity without potential negative group process losses that could undermine study results.

Control group procedures. The BDG consists of a simple four-tier supply chain in which each participant in a team of four plays the part of inventory manager for one of four supply-
chain tiers: retailer, wholesaler, distributor, and factory. Each tier inventory manager orders inventory independently from the other supply-chain tier managers, using only the inventory order information from the immediate downstream supply-chain member.

Consumer demand was simulated by using pre-defined levels of consumer demand and was the same for each instance the BDG was played. As retail inventory levels are depleted through customer sales, the retail inventory manager orders more inventory from the distributor. The distributor in turn orders inventory from the factory warehouse and so on. In making decisions about how much inventory to order, each tier manager is allowed to view and utilize only the order information available from the immediate downstream supply-chain member. Given varying customer demand, each tier must order a level of safety stock so that costly stockouts do not occur. However, if too much safety stock is on hand, the tier will incur a per-item inventory holding cost. The holding cost for each item of inventory is $2, while the stockout cost per inventory item is $4. The object of the game is to minimize holding and stockout costs as a team, or in other words, to become an efficient supply chain.

In administering the game, each subject was randomly assigned a role as a retailer, wholesaler, distributor, or factory. After the rules of the game were explained, the game’s distribution channel was initialized in equilibrium. Each tier had an inventory of 12 cases of beer, and the supply-chain throughput was four cases per week to match consumer demand, which was also four cases per week initially. During the first four rounds, customer demand remained the same as the participants became accustomed to ordering for their respective tier. For the first three rounds, participants were instructed to order four cases; in the fourth round, participants could order any positive amount. However, in the fifth round there was an unannounced increase in consumer demand to eight cases. This increase in demand created disequilibrium in the supply chain to which the participants had to adjust. In the game’s
instructions, the participants were told the game would continue for 50 rounds; however, following Sterman’s suggestion the game was halted after round 36 to avoid horizon effects.

Each tier had only local information available; each subject could see only the order size of the next downstream tier. In Sterman’s (1989) study of 48 teams (consisting of 192 participants), customer demand information represented by retail orders invariably became distorted as each successive tier added a measure of safety stock to the order. The information distortion within the supply chain caused broad swings in inventory levels from inventory shortages to surpluses, with the top-most tier (factory) always being most affected. At the end of all 36 rounds, the holding costs and stockout costs were tallied for the team as a whole (all four tiers) and recorded.

_Treatment group procedures._ The BDG model for the experimental group was modified by simulating information available through an RFID-enabled supply chain. The experimental group played the BDG in precisely the same manner of execution as the control group; however, the experimental computer program simulated the use of RFID technology by displaying the flow of all inventory cases from the lowest supply-chain tier (retailer) to the highest tier (factory). Whereas the supply-chain interface of the control group was effectively a “black box,” providing no information beyond the subject’s immediate tier, the interface of the experimental group afforded full transparency of the supply chain. For example, as soon as the subject playing the role of retailer—the bottom-most tier—placed an order, the order information was immediately apparent to the subject playing the top-most tier role of factory.

We operationalized five choices in our implementation of the BDG to enhance the likelihood that the bullwhip effect would occur:

1. Limited global information—participants are ignorant of how much inventory is available at other tiers as well as the level of demand facing other tiers.
2. Delay in signal—the time required for an inventory order to arrive at the next upstream tier (four rounds).
3. Delay in inventory to arrive—the time required for ordered inventory to reach the next downstream tier (an additional four rounds).

4. An unexpected 100% increase in customer demand—the inventory demanded by the consumer jumps from four units of inventory to eight, where it subsequently remains until the end of the game.

5. Uncoordinated order decisions—participants cannot communicate with one another, thereby preventing team strategies to form.

Each of the above five factors contributes to the occurrence of the bullwhip effect, and together make the occurrence of the bullwhip effect almost inevitable and practically impossible to mitigate. In fact, Sterman’s (1989) observations of performing the BDG over the span of many years revealed that the bullwhip effect always occurred to some degree when the game was administered. By simulating the transparency provided by RFID (Karkkainen, 2003), two of the five factors contributing to the occurrence of the bullwhip effect, as described above, are removed: limited global information (factor one) and, following as a natural consequence, the delay of signal (factor two). Given the current literature on the potential of RFID technology to provide both instantaneous and global supply-chain information (Kinsella, 2003), removing these two factors seems consistent with the capabilities of proposed RFID-enabled supply-chain systems. Rather than having to count inventory levels manually, RFID-enabled warehouses can quickly scan the warehouse and determine its exact contents on a real-time basis. To accomplish roughly the same task using barcodes, each individual item would need to be scanned either manually or by physically running the item through an automatic barcode reader. Karkkainen (2003) notes the benefits of additional information available through RFID:

*Efficient capture of data in the supply chain helps to track channel inventory and sell-through. This provides transparency of the supply chain and, thus, helps create more accurate forecasting and supports the optimization of stock replenish quantities. Increased visibility also helps in timing replenishment more accurately. Visibility and the opportunity to interrogate the distribution chain also enable detecting shortages and overstock as they occur and, thus, helps in reacting before threats materialize (p. 530).*

Although the simulated RFID-enabled supply chain removed two factors influencing the
occurrence of the bullwhip effect (limited global information and delay in signal), the remaining three contributing factors were held constant (delay in inventory to arrive, an unexpected 100% increase in customer demand, and uncoordinated order decisions). These three factors significantly contributed to the occurrence of the bullwhip effect, preserving the utility of the BDG to produce the bullwhip effect.

Not only did this added information provide each supply-chain member with real-time inventory information, but a continuous consciousness of the whole supply chain was also created. This full awareness of the supply chain greatly increased the agility of the supply chain as a whole as inventory managers were able to make better inventory decisions, thus simulating the benefits of added real-time information provided by RFID. Near-perfect information visibility is one of the key aspects of RFID (Angeles, 2005) that our design operationalizes. In fact, EPCglobal (one of two primary RFID standards setting groups) proposed an Internet-based supply-chain model aimed at improving supply-chain end-to-end visibility through RFID (Asif & Mandviwalla, 2005).

ANALYSIS

Since all hypotheses involve predictions over time, we averaged and compared the control and treatment data over the 36 rounds. Given the number of participants, teams and data drops, this allowed for 1,173 usable data points. Table 1 summarizes the means that were used as the basis for the statistical comparisons. It was possible to have negative levels of inventory quantity due to stockouts; also, the beer game imposed a significant stockout fee (2x that of normal inventory costs), which increased the total inventory costs. Negative inventory cost the tier $4 per negative unit (stockout cost) while positive inventory cost $2 per positive unit (holding cost). We then performed multivariate ANOVA on all measures to provide statistical adjustments for the fact that we were performing multiple comparisons. The overall model tested
significant at $F_{(4, 1168)} = 28.72 \ p = 0.000$. The specific results of each hypothesis, as analyzed by tests of between-subjects effects, are in Table 2.

**Table 1. Means of Control and Treatment groups**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Descriptive statistics</th>
<th>Total inventory on hand (units)</th>
<th>Average deviation in total inventory (unit)</th>
<th>Total inventory costs ($)</th>
<th>Average deviation in inventory costs ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Mean 393.2 units</td>
<td>320.3 units</td>
<td>$3,360.9</td>
<td>$879.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N 552</td>
<td>552</td>
<td>552</td>
<td>552</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD 1774.7 units</td>
<td>661.4 units</td>
<td>$6,566.4</td>
<td>$1,857.2</td>
<td></td>
</tr>
<tr>
<td>Treat</td>
<td>Mean 66.8 units</td>
<td>57.4 units</td>
<td>$653.87</td>
<td>$148.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N 621</td>
<td>621</td>
<td>621</td>
<td>621</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD 184.6 units</td>
<td>76.7 units</td>
<td>$805.36</td>
<td>$216.35</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2. Tests of Between-Subjects Effects**

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Hypothesis</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean square</th>
<th>F</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total inventory on hand</td>
<td>H1</td>
<td>31135580.2</td>
<td>1, 1173</td>
<td>31135580.2</td>
<td>20.75</td>
<td>*0.000</td>
</tr>
<tr>
<td>Average deviation in total inventory</td>
<td>H3</td>
<td>20187889.9</td>
<td>1, 1173</td>
<td>20187889.9</td>
<td>96.60</td>
<td>*0.000</td>
</tr>
<tr>
<td>Total inventory costs</td>
<td>H2</td>
<td>2141533815.3</td>
<td>1, 1173</td>
<td>2141533815.3</td>
<td>103.80</td>
<td>*0.000</td>
</tr>
<tr>
<td>Average deviation in inventory costs</td>
<td>H4</td>
<td>156489389.5</td>
<td>1, 1173</td>
<td>156489389.5</td>
<td>94.97</td>
<td>*0.000</td>
</tr>
</tbody>
</table>

** = significant at $\alpha = 0.01$

To summarize, since the results showed that RFID systems have lower inventory levels across the four tiers over time than traditional supply-chain systems, H1 was supported. The results also showed support for H2; the RFID systems indeed had lower total inventory costs across the four tiers over time than traditional supply-chain systems. Since the RFID systems had lower variations in inventory levels across the four tiers over time than traditional supply-chain systems, H3 was also supported. Finally, H4 was also supported since the RFID systems had lower variations in inventory costs across the four tiers over time than traditional supply-chain systems.
systems.

DISCUSSION

All of the predicted hypotheses from this study were supported. Namely, over time the simulated RFID-enabled groups had less total inventory on hand, less total inventory costs, less variation in inventory levels, and less variation in inventory costs. Not only were there significant differences in the means but the results were very relevant to practice. Notably, the standard deviations in the RFID treatment groups were much smaller than the standard deviations in the control supply-chain groups. The differences in variability partially show the unpredictability caused by poor information sharing in bullwhip effect conditions. We depict this variation graphically over the 36 weeks in Figure 5 (control) and Figure 6 (treatment). The difference in the variation between the control and treatment groups was so large that they could not be depicted in the same graph because of the scale difference. The important trend to note is that the variations in the control group are not very problematic until around week 15, when the variations start to bullwhip dramatically and become unrecoverable. Meanwhile, the treatment group was able to maintain very small variations over time overall, with only occasional spikes in inventory levels due to the bullwhip effect. However, in each case the treatment group was able to correct the inventory levels in a coordinated way.
Figure 5. Variations in Inventory Amounts in Control (non-RFID) Groups over Time
Figure 6. Variations in Inventory Amounts in Treatment (RFID) Groups over Time

From the above results, it is apparent that the RFID-simulated experimental group was better able to adapt to the change in consumer demand as well as to each supply-chain member’s independent inventory orders. It is interesting to note that at three points in the simulation (weeks 7, 17, and 21), large and sudden increases in inventory occurred. We offer two explanations for this result.

First, the BDG is designed to create the bullwhip effect, not only by limiting information among supply chain members and abruptly increasing inventory demand levels, but also by its relatively rapid and lock-step pace (Sterman, 1989). Thus, the fact that the bullwhip effect was experienced to a limited degree is not surprising. Second, Croson and Donahue (2006) found that the bullwhip effect can occur even after demand estimations and price fluctuations are removed. However, what is more important is that participants in the RFID were able to correct the excess in inventory in a coordinated way.
Because of continual supply-chain information available from the production of inventory to its eventual sale, the experimental RFID-simulated group was able to act more closely as an integrated whole rather than as four disjointed units or parts. In contrast, without this added information, it was impossible for the supply-chain members of the control group to achieve any level of coordination.

**Contributions**

From the perspective of business agility, RFID technology holds tremendous promise to increase supply-chain cohesion and decrease variation characterized by the bullwhip effect, including across interorganizational systems. Managing inventory through several distinct and often divergent supply-chain tiers is a major challenge. With such conditions, any coordination among supply-chain tiers is a success. However, given the volatile electronic marketplace and increasing pressure from competitors, inventory supply chains must become increasingly agile to remain competitive and relevant to the consumer’s needs. The promise of RFID technology is to enable a supply chain to act as a cohesive unit—to readily provide inventory information throughout the supply chain. It is this panoptic capability that gives RFID technology the potential to mitigate information distortion and the ensuing bullwhip effect to a greater extent than has previously been possible. Whereas previous supply-chain simulation studies have shown the benefits of sharing information (2006), this study makes a unique contribution by showing the effects of giving full visibility to both upstream and downstream supply-chain members simultaneously (Atock, 2003; Kinsella, 2003), which is critical in e-commerce (Yang, et al., 2001). Further, the simulation used in this study provided supply-chain members with full visibility of both inventory at all supply chain tiers and inventory en route. This greater visibility more fully simulates the capabilities of RFID (Lee & Ozer, 2007).

Because RFID is an emerging technology and its influence on the bullwhip effect remains largely unobserved, this study offers a contribution by providing empirical evidence that RFID
technology can reduce the bullwhip effect to a significant degree. It is hoped that this study will help form a basis for further study of RFID’s unique promise to reduce the bullwhip effect and to tremendously benefit interorganizational e-commerce systems and relationships with trading partners.

Given the above-mentioned expectation for RFID technology to revolutionize the supply-chain system, some may find the above results highly intuitive. Indeed, the idea that timely and pertinent information can enhance the efficiency of a supply chain is not only intuitive but also foundational to logistic information systems and the field of information systems in general. However, despite how axiomatic the above results may appear, the potential of RFID technology to mitigate the bullwhip effect and increase supply-chain agility in general should nevertheless be further explored and empirically studied. If the above-stated predictions are even partially accurate, the benefits of RFID technology merit a thorough understanding as its use unfolds. Without such pre-explored knowledge, RFID technology may be misapplied, and the promise of effectively mitigating the bullwhip effect and increasing business agility of a supply chain as a whole may take longer to realize.

**Limitations and Future Research**

Future studies of the application of RFID technology to different e-commerce situations would certainly strengthen this study’s external validity. As an abstract simulation, the RFID-enabled BDG is obviously limited in its generalizability. However, on this point Sterman (1989) gave this insight into his initial research utilizing the BDG: “The experiment, despite its rich feedback structure, is vastly simplified compared to the real world. To what extent do the experimental conditions and results apply? First, would participants’ behavior differ if customer demand follows a more realistic pattern, e.g. noise and seasonality? The order decisions of many subjects were in fact noisy and cyclic” (p. 336). Sterman also explains that although managers in the real world have access to more inventory information than the subjects in the experiment,
“information in the real world is often out of date, noisy, contradictory and ambiguous” (p. 326). Therefore, the generalizability of this study, though limited, may be greater than it ostensibly appears.

A further limitation to the validity of the present study is the lack of real-world, RFID-enabled, supply-chain data to verify the results of the simulated RFID-enabled supply chain of the experimental group. The validity of the traditional BDG in describing the bullwhip effect has been strengthened by agreement with expert opinion of supply-chain domain professionals and data observed from the bullwhip effect in actual supply chains. The findings of the present study can also be strengthened by similar calibration of data provided by actual RFID-enabled supply-chain systems when such systems become more widely implemented. Many process and information system details still need to be resolved in regard to RFID. Examples of such areas of improvement and future research include delivery performance, fill rate, perfect order fulfillment, order fulfillment lead time, supply-chain response time, productive flexibility, supply-chain management cost, cost of goods sold, value added productivity, warranty cost or returns processing cost, cash-to-cash cycle time, inventory days of supply, and asset turns (Bose & Pal, 2005).

Though RFID tags are a technological commodity, their use does not guarantee success. An important related limitation and assumption in this research is our assumption of a perfect information system in our simulation. It is one thing to say we need increased visibility across supply chains to mitigate the bullwhip effect (Olhager, 2002), but in practice, delivering visibility through technology is a non-trivial and highly strategic e-commerce task (Yang, et al., 2001). No more true is the claim by Goldman et al. (1995) that agility depends largely upon an organization’s (or supply chain’s) ability to utilize advanced, computer-based technologies. Srivastava (2004) clearly summarizes the link between information systems and supply-chain
agility:

What is required is visibility across several dimensions—demand patterns, order status, inventory at all levels, production schedules, sales/marketing initiatives, and so on—of the supply chain, with technology playing a greater role in communications and in the seamless integration of collaborative decisions into the partners’ business processes. Automatic electronic sharing of the data serves to speed up the workflow, enabling more activity to proceed in parallel while remaining synchronized. Data synchronization in supply chains will prevent errors due to miscommunication and can lead to tremendous benefits in terms of transactional efficiencies. (p. 63)

Accordingly, developing sophisticated information systems to support RFID may be the biggest hurdle to successful implementation of RFID, because it can only “succeed if it is supported by a software system capable of consolidating the large amount of data captured by the wireless readers” (Bose & Pal, 2005). We add that data consolidation is necessary but not sufficient; RFID requires extensive use of data mining to make use of automatically acquired data (Bose & Pal, 2005). RFID needs to be integrated throughout a corporation’s information systems, which will likely require sophisticated integration with Enterprise Resource Planning (ERP) software and Web services, the creation of middleware, and so forth (Bose & Pal, 2005). Finally, RFID requires use of experienced supply-chain managers and expert systems who know what to do with the produced information and knowledge.

Moving beyond the limitations of this study, new developments in RFID tags provide for several new areas of research. For example, RFID tags are being developed that do not need their own power source; instead, using specialized readers, they are illuminated through actual radio waves (Borriello, 2005). As a result of this development, Gaetano Borriello states that “We can imagine a future where passive RFID tags are in every manufactured object and maybe even in some non-manufactured ones (such as natural resources, animals, and people)” (Borriello, 2005, p. 36). Other researchers are developing ways to create tags that can transmit geographic tag location and location history (Raskar, Beardsley, Dietz, & Baar, 2005). Recognizing the
ubiquitous future of RFID tags for tracking parts and people, RFID security and consumer privacy are becoming increasingly important foci of research, with several different technological solutions being investigated (Ohkubo, Suzuki, & Kinoshita, 2005). The implications of such future RFID developments on the bullwhip effect, supply chains, integrated information systems—and for society in general—are quite profound and provide many exciting research opportunities.

CONCLUSION

This study indicates that RFID technology has significant potential to increase supply-chain agility and mitigate the bullwhip effect through additional and enhanced information that RFID uniquely provides. This has particularly important implications on interorganizational e-commerce supply chain systems, where pressure from trading partners is acute (Chi, et al., 2007; Hsu, et al., 2006). Finding ways to proactively manage the supply chain electronically and to reduce uncertainty and errors has long been a goal of e-commerce (Bodendorf & Zimmermann, 2005; Ho, et al., 2005). We posit and show evidence that RFID is a key technology that will help with this proactive management. Our findings show that participants in the experimental group were better enabled to act as a coordinated unit and thus were able to avoid the large variations endemic to the bullwhip effect to a much greater extent than were the participants of the control group. This was demonstrated by the experimental group’s lower inventory costs, lower incoming inventory, lower orders to fulfill, lower total orders placed, and inventory levels closer to zero. Additionally, our analysis shows that the amplification of order and inventory variances, a key characteristic of the bullwhip effect, was less evident in experimental group supply chains than in the supply chains of the control group. Together, these findings strongly suggest that enhanced information provided by RFID technology can minimize the bullwhip effect. These findings have great potential value because the use of RFID tags is exploding into supply-chain
and e-commerce areas not previously envisioned.

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REFERENCES


