Newsvendor Pull-to-Center Reconsidered

Nelson Lau
J. Neil Bearden
Sameer Hasija
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Nelson Lau *

J. Neil Bearden**

Sameer Hasija***

* PhD Candidate in Decision Sciences at INSEAD 1, Ayer Rajah Avenue, Singapore 138676, Singapore. Email: nelson.lau@insead.edu

** Associate Professor of Decision Sciences at INSEAD 1, Ayer Rajah Avenue, Singapore 138676, Singapore. Email: neil.bearden@insead.edu

*** Assistant Professor of Technology and Operations Management at INSEAD 1, Ayer Rajah Avenue, Singapore 138676, Singapore. Email: sameer.hasija@insead.edu

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Nelson Lau
INSEAD, nelson.lau@insead.edu

J. Neil Bearden
INSEAD, neil.bearden@insead.edu

Sameer Hasija
INSEAD, sameer.hasija@insead.edu

Abstract

In the newsvendor problem, a pull-to-center effect has been asserted, whereby subjects are said to order a quantity between the mean of the demand distribution and the expected profit-maximizing quantity. These claims have only been examined using group-level aggregate statistics. Looking at individual-level data from an previously published study and a new experiment, the current paper shows that while pull-to-center is present in aggregate data, it does not adequately describe the population of individual decision makers, who are found to be highly heterogeneous. Methodological implications and future research directions are discussed.

Key words: Behavioral Operations Management; Newsvendor Problem; Pull-to-center; Measurement and Methodology; Experimental Economics

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1. Introduction & Background

Extant literature has asserted the existence of a pull-to-center effect in empirical newsvendor behavior (see Schweitzer and Cachon 2000, Benzion et al. 2008, Bolton and Katok 2008, Bostian et al. 2008, Lurie and Swaminathan 2009, Kremer et al. 2010, among others). This implies that instead of ordering the expected profit maximizing quantity (q*), actual subjects order a quantity between q* and the mean of the demand distribution (\( \bar{d} \)).

Research to date has assumed that the pull-to-center effect is a characteristic property of individual behavior. For example, Schweitzer and Cachon (2000) stated that “subjects consistently order amounts lower than the expected profit-maximizing quantity for high-profit products and higher than the expected profit-maximizing quantity for low-profit products” (p.418).

Based on this assumption, attempts have been made to explain the pull-to-center phenomenon. Individual decision making rules such as the “mean anchor heuristic” (Schweitzer and

\[ ^{1} \text{See the textbook by Cachon and Terwiesch (2009), among others, for the newsvendor problem and its solution.} \]
Cachon 2000, p. 409) have been proposed. Design factors such as the uncensored presentation of demand information have been advanced as explanations (Rudi and Drake 2010). Models of individual ordering behavior based on bounded rationality have been suggested, with some success at replicating a pull-to-center ordering pattern (Su 2008).

Attempting to explain a phenomenon presumes its existence. However, evidence for pull-to-center has been based on aggregate data. For instance, Schweitzer and Cachon (2000) reported that in Experiment 1, “the average order quantities across all inventory decisions… exhibited the too low / too high pattern” (p. 411), while in Experiment 2, “the average order quantities under the low-profit condition [were] significantly above the expected profit-maximizing quantities” (p.415).

Aggregate averages can be misleading. If a distributor has a customer pool that are 50% small retailers buying products in 100-unit orders and 50% large retailers buying products in 10,000-unit orders, the average order size is 5,050. However, this average is not representative of the population, and describes a type of customer who does not exist (example derived from Savage 2009).

The current paper demonstrates that the same is true of newsvendor behavior. When group data are averaged, pull-to-center is observed. However, inspecting individual data reveals that ordering behavior is heterogeneous, and that pull-to-center is not a universal phenomenon.

2. Experimental Evidence

Two sources of data are used in the current paper. The first is Study 1 of Bolton and Katok (2008). These authors presented 20 subjects with a low margin newsvendor problem and 18 subjects with a high margin problem, both for 100 seasons of demand. The second is a new experiment conducted based on Schweitzer and Cachon (2000). 94 participants were presented with a low margin set-up and 80 participants with a high margin set-up, both for 20 seasons of demand. Subjects were from Amazon Mechanical Turk (AMT), and compensation was awarded in an incentive compatible fashion (see Kittur et al. 2008, Mason and Watts 2009, Horton et al. 2010, and Paolacci et al. 2010 on the reliability of AMT for experiments).¹

2.1 Aggregate Summary Statistics

Table 1 displays the mean orders for all four experiments. In every case, the average subject’s order lies in the open interval bounded by \( \overline{d} \) and \( q^* \). The difference between the mean order and \( q^* \) is subjected to a Wilcoxon signed-rank test, and the p-value in every experiment indicates statistical significance. Pull-to-center is observed in aggregate data.

¹ Henceforth, BKL will refer to the low margin condition experiment of Study 1 in Bolton and Katok (2008) and BKH to the high margin condition of the same. MTL will refer to the low margin condition experiment of the new experiment and MTH to the high margin condition of the same.

² Henceforth referred to as the PTC zone.
2.2 Individual Histograms

If pull-to-center characterized individual behavior, and there was no variability in ordering, then the histograms of individual orders would all be mass points at a quantity in the PTC zone. Incorporating variability in orders, each histogram should be a distribution with mean in the PTC zone, and some noise around this mean. If the ordering process is thought to follow a quantal choice model such as in Su (2008), or if variance in orders is believed to simply be noise around a target order quantity, then each individual histogram of orders can be expected to follow a truncated normal distribution.

Figure 1 shows the histograms of individual orders in BKL. There is significant heterogeneity in behavior. Subjects 6 and 15 order exclusively above the PTC zone; Subjects 13 and 14 order exclusively below the PTC zone; Subjects 1 and 2 order q* in virtually all seasons. Although summary statistics (Table 1) show the pull-to-center on group-level data, examining individual data reveals it to be less common than previously thought. Figure E1 to Figure E10 in the electronic companion show the individual histograms for BKH, MTL, and MTH. These figures again indicate subject heterogeneity and the substantial absence of pull-to-center in individual data.

2.3 Percentage of Orders in PTC Zone

From a definitional standpoint, if pull-to-center characterizes an individual’s ordering behavior, then it is fair to expect that participant’s order quantity distribution to be concentrated within the PTC zone.\(^4\)

The mean anchor heuristic proposed by Schweitzer and Cachon (2000) – “a decision maker anchors on mean demand and adjusts towards the optimal order quantity” (p.409) – is both a proposed explanation for and definition of pull-to-center. If this holds, individuals’ orders should lie exclusively in the PTC zone. Allowing for random errors in ordering decisions, the majority of individuals’ orders should still lie in the PTC zone.

Figure 2 shows the histogram of subjects by their percentage of orders in the PTC zone. For example, in BKL, the leftmost bar with a height of 50% means that half of the subjects placed between 0% and 10% of their orders in the PTC zone, and thus 90% to 100% of their orders outside the PTC zone.

If pull-to-center is present in individual ordering, then in Figure 2, almost all the mass should be on the right in each graph. Using a generous definition – that pull-to-center applies to an individual when 50% or more of their orders are in the PTC zone – only 35% of subjects in BKL, 33% in BKH, 24% in MTL, and 15% in MTH can be said to exhibit pull-to-center.

2.4 Mean, Median, and Modal Order Quantities

A looser definition of pull-to-center would be that an individual’s average order quantity lies in the PTC zone. This would also follow as a consequence of the mean anchor heuristic.

\(^4\) Subsequent subsections will consider even looser definitions of pull-to-center.
Figure 3 shows the cumulative distributions of subjects’ average order quantities. The average is calculated using the mean, median, and mode, as displayed in the top, middle, and bottom rows respectively. The left column displays BKL and MTL; the right column displays BKH and MTH. Vertical lines on the plots indicate the boundaries of the PTC zone.

Thus, 30% of subjects in BKL, 28% in BKH, 45% in MTL, and 33% in MTH have mean orders outside the PTC zone. 55% of subjects in BKL, 39% in BKH, 48% in MTL, and 61% in MTH have median orders outside the PTC zone. Finally, 65% of subjects in BKL, 56% in BKH, 66% in MTL, and 76% in MTH have modal orders outside the PTC zone. These percentages indicate subjects who do not exhibit pull-to-center.

2.5 Bostian α-coefficients

Bostian et al. (2008) operationalize the mean anchor heuristic as:

\[ q_t = \bar{d} + \alpha(q^* - \bar{d}) + \varepsilon, \]

where \( \alpha \) reflects the “extent of rationality” i.e., how far subjects deviate from the mean of the demand distribution towards \( q^* \) (p. 594). Regressing \( (q_t - \bar{d}) \) on \( (q^* - \bar{d}) \) thus yields the “Bostian α-coefficient,” which must lie in \((0, 1)\) to be consistent with mean anchoring and consequently pull-to-center.

Figure 4 shows the cumulative distribution of α-coefficients obtained from individual regressions. 30% of subjects in BKL, 28% in BKH, 33% in MTL, and 45% in MTH have α-coefficients outside \((0, 1)\), which is not consistent with pull-to-center. Looking at the p-values of the coefficients, there are just 60% of subjects in BKL, 56% in BKH, 46% in MTL, and 32% in MTH with α-coefficients inside \((0, 1)\) that are significant at the 0.05 level.

2.6 Convergence

Benzion et al. (2008) study learning and convergence, asserting that orders “converge to a value between the mean demand and the quantity for maximizing the expected profit” (abstract). If this alternate definition of pull-to-center holds in individual data, then in the final seasons of the experiment, subjects should be observed ordering quantities in the PTC zone.

Figure 5 shows the percentage of subjects whose mean orders over a specified number of final seasons lie in the PTC zone. For example, the datapoints on the left of the graph (1 season remaining) indicate the percentage of subjects whose very last order is in the PTC zone.

In the terminal season, only 30% of subjects in BKL, 33% in BKH, 38% in MTL, and 18% in MTH placed orders in the PTC zone. Across all four experiments, varying the number of ending seasons examined, between 28% and 83% of subjects converged to mean orders outside the PTC zone.
3. Conclusion

The following statement summarizes the current paper:\textsuperscript{5}

\begin{quote}
What was thought to be a single phenomenon is in reality composed of assorted heterogeneous elements.
\end{quote}

Drawing conclusions about individual behavior from aggregate data invokes an implicit representativeness assumption. In some instances, this can be misleading (see the discussions in the Mathematical Psychology and Psychonomics literature – Sidman 1952, Bakan 1954, Estes 1956, Estes 2002, Estes and Maddox 2005, among others). However, there exist situations in which it is appropriate to make inferences from group data (a recent example is Ovchinnikov et al. 2011). To differentiate between the two cases, it is important to assess the heterogeneity in individual responses, and the extent to which aggregate summary statistics are representative of the variety of agents’ behaviors. In short, the representativeness assumption must be verified.

To be clear, simplification need not be avoided. It is important in advancing theory and knowledge, especially as part of model building. The concern is whether the suggested simplification is appropriate (see Anderson 2011 for a valuable discussion).

Pull-to-center may be an inappropriate simplification.

Imagine a model of behavior based on pull-to-center were adopted. A distributor of goods faces a retailer population similar to Figure 1, and makes decisions based on this model. The distributor would end up acting sub-optimally when facing retailers like Subjects 1, 2, 6, 13, 14, or 15, among others. More broadly, based on the analyses in §2.3 to §2.6, a pull-to-center model would be inaccurate when dealing with a very significant proportion of actual agents.

Going forward, heterogeneity in newsvendor behavior should be recognized. This acknowledgement can open new avenues for research, as exemplified by Wu and Chen (2011), who parameterized newsvendor types and analyzed the optimal contract type based on the value of the type parameter. This can add a layer of richness and realism to behavioral research.

The pull-to-center effect does not accurately describe individual behavior. That implies that models based on it cannot even function as “useful fictions” or “as-if” models (MacDonald 2003, Berg and Gigerenzer 2010). Predictions of subject behavior based on pull-to-center are inaccurate. Thus, it is not a useful starting point for investigating individual decision making in the newsvendor problem, and should be reconsidered.

\textsuperscript{5} We believe that this is an important observation because it is an instance of “what was thought to be X is really Y,” as per Cachon (2011) or Davis (1971).
References


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Bolton & Katok 2008 - Study 1 (Low Margin Condition)

Figure 1 – Histograms of individual ordering distributions in BKL
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Figure 2 – Percentage of orders in PTC zone

Figure 3 – Mean, median, and modal orders
Figure 4 – Bostian $\alpha$-coefficient

Figure 5 – Convergence
### Tables

<table>
<thead>
<tr>
<th>Experiment</th>
<th>d</th>
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*Table 1 – Aggregate Summary Statistics*
Europe Campus
Boulevard de Constance
77305 Fontainebleau Cedex, France
Tel: +33 (0)1 60 72 40 00
Fax: +33 (0)1 60 74 55 00/01

Asia Campus
1 Ayer Rajah Avenue, Singapore 138676
Tel: +65 67 99 53 88
Fax: +65 67 99 53 99

Abu Dhabi Campus
Muroor Road - Street No 4
P.O. Box 48049
Abu Dhabi, United Arab Emirates
Tel: +971 2 651 5200
Fax: +971 2 443 9461

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