Optimal Information Acquisition
For Firm Decisions

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Abstract

Firms face increasing uncertainty and are confronted with an explosion of available data ignited by advances in information technology. Acquisition and management of information has become a major strategic task for a firm that wants to remain competitive. Though it has access to more detailed data than ever before, a firm lacks resources and time to process all data into insights useful for decision making. Consequently, it must decide which data to process and which to ignore, i.e., how to allocate its limited resources.

The optimal allocation of resources involves two kinds of decisions. First, a firm must decide which factors of a business environment, such as customer preferences, production costs, competitor behavior, economic conditions, etc. deserve attention. Second, it must decide whether it should develop detailed insights about a few of these factors or gain a broad understanding of all of them. In other words, it must trade off depth of information with breadth of information.

This paper is the first attempt in marketing to study these tradeoffs required for the optimal acquisition of information. Specifically, we are interested in answering the following questions: (1) Should competing firms prefer broad or detailed information? (2) What is the effect of firm and market characteristics, like the degree of uncertainty, the competitiveness of markets, or a firm's effectiveness in processing data? A better understanding of what data a firm should process is important for helping firms to cope with the information revolution and for assessing actual behavior. Moreover, these insights about "customer behavior" are of value to data sellers.

To answer these questions, we develop a game-theoretic model that consists of firms facing uncertainty about external conditions (i.e., market demand) and internal conditions (i.e., the firms' cost). The firms have access to data to learn more about these uncertain conditions and make better decisions. The transformation of data into information requires firm resources (e.g., management time) that are fixed and insufficient to process all data. The more resources allocated to some data, the more accurate the resulting information. Given the lack of resources, more accurate information about external conditions must be "bought" with less accurate information about internal conditions, and vice versa.

The main finding of this paper is that often *firms should prefer detailed information to broad information, in particular when uncertainty is limited, competition is high, and firms' effectiveness in processing data into information is high.* Preferring depth over breadth of information is optimal even without differences between external and internal factors with respect to uncertainty or effectiveness in processing data. In equilibrium, when one firm focuses its resources on data about external conditions, a second identical firm always focuses on data about internal conditions.

This paper makes a number of important contributions to our understanding of a firm's information acquisition. First, it provides a framework grounded in economic theory to examine the allocation of resources to improve a firm's understanding of different factors that affect its future profits. Second, it offers a normative explanation for why firms sometimes ignore data about some factors that seem valuable and makes predictions under what conditions we should observe such behavior. For example, early in the product life cycle firms more likely prefer broad to detailed information, while in mature markets the preference should be reversed. However, there is no unambiguous rule of thumb for firms in many industries with increasing uncertainty, higher competition and rapid advances in information technology. Finally, the paper yields insights for data providers who need to assess the demand for different types and qualities of information. For example, in a highly uncertain environment a data provider should offer data about many factors rather than specializing into offering very complete data about a limited number of factors.

(Information Acquisition, Strategic Decision Making, Game Theory)

"The fox knows many little things, but the hedgehog knows one big thing."

Archiluchus, Greek Poet

1. Introduction

Imagine a firm that is developing a new generation of widgets. The schedule for the product launch requires the firm to commit soon to the location and the size of the production facility for the widgets. Yet, the various forces that drive the impact of this decision on the firm's future profits are not fully understood. In particular, the firm is uncertain about the market potential, the production process, and the costs of input factors. However, the firm has access to data, such as reports from numerous internal cost and external market studies, to better understand these factors. Unfortunately, it lacks time and resources for paying full attention to all available data. By using more time and postponing the decision, the firm could fall behind its competitor. Increasing resources is not feasible in the short run. Consequently, it must decide which data to study in more detail and which to ignore. In other words, it must decide how to allocate its resources to data about demand conditions and to data about cost conditions. How should the firm make this decision? What is the optimal allocation of resources?

Acquisition and management of information has become one of the most important strategic issues for firms due to advances in information technology and increases in business uncertainty. According to Simon (1993), the allocation of managerial resources to learn about trends and events that matter most to a firm's future is a major strategic function of a firm. In a survey among European managers, 89% of the respondents indicated that knowledge is key to business success and gaining a competitive advantage its most important application (Murray and Myers 1997). Though firms today have access to larger amounts of more detailed and timely data than ever before, the typical firm is neither willing nor able to process all data to generate information (e.g., Deshpandé and Zaltman 1982; Simon 1957). Information technology provides little help since advances in data processing significantly lag advances in data collection and transmission (Blattberg, Glazer and Little 1994). As a result, there is considerable value in better understanding the widget firm's information acquisition problem, for academics to study firm behavior, for consultants to help firms with similar problems, and for data providers to understand "consumer" behavior.

Though research concerning information processing and utilization for firm decisions has increased considerably over the past years, relatively little attention has been devoted to the subject of *how a firm should trade off detailed (deep) insights about a few business factors with a broad understanding of many business factors*. In other words, we do not know whether the widget firm should advise its managers to study some market reports and some cost reports or to concentrate on as many market (cost) reports as possible during the limited time available. In hindsight firms are often criticized for paying insufficient attention to some factors. For example, American car manufacturers underestimated their Japanese competitors. Firms like Sears and IBM lost sight of their customers (Fortune 1993). However, we have little normative guidance to assess a priori firms' information acquisition behavior.

The objective of our paper is to fill this gap by developing a game-theoretic model to study a firm's information acquisition problem. In particular, we are interested in answering the following questions: (1) Should competing firms prefer broad information to detailed information? (2) What is the impact of firm and market characteristics, like the degree of uncertainty, the competitiveness of a market, or a firm's effectiveness in processing data?

The next section describes the information acquisition problem in more detail and relates our paper to the relevant literature. In §3, we formally develop the model and provide the analytic solutions of the two-stage game. Insights from a number of model extensions and potential limitations of our research are discussed in §4. The paper concludes with a summary of the results and a discussion of their implications.

2. Information Acquisition

2.1 The Problem with the Information Revolution

Effective management of information has become a business imperative and is a source of substantial potential advantages. For example, Wal Mart's position as the leading retailer in the US is typically attributed to its superior information management. Information technology allows Charles Schwab to improve its competitive position by continuously redefining the retailing of financial products. Retailers offer customer loyalty cards not only to influence store switching, but primarily to collect household shopping data. HMOs look for new opportunities to capitalize on their large databases of patient records. Citibank Visa uses records of past transactions to detect the fraudulent use of its credit cards. Information technology enables firms to target smaller and smaller market segments, i.e., to "mass-customize" their products, and to transform advertising from unfocused broadcasting to two-way communication with customers (Blattberg and Glazer 1994).

What exactly constitutes information is not clear (see for example Machlup and Mansfield 1983). In this paper, we follow the definition that is commonly used in the literature and consider *information as data that have been interpreted into a form meaningful to users* (Blattberg et al. 1994). In addition, we do not make a formal distinction between knowledge and information.

Despite the strategic importance of information, the potential of the information revolution seems largely untapped. One of the most newsworthy marketing trend is the success of everyday low pricing (EDLP), a retailing strategy which requires relatively little information to implement. The full impact of the information revolution is not impeded by the quality of the data, but by the exploding quantity. In marketing we tend to emphasize the explosion of external market data.

- According to IRI, a single category file contains about 50 million bits of information. It takes a human mind at peak attention more than 19 weeks of full-time effort to review the data (Kelly 1994).
- A consumer packaged goods brand manager in the US is confronted with 2 million new numbers each week (McCann and Gallagher 1990).

- The amount of electronically stored data within the typical "Fortune 500" firm is estimated to grow to 400,000 Gigabytes (Gb) in 2000 from 350 Gb in 1980 (Information Week 1994).

Yet, it is estimated that 90% of the accumulated data relate to a firm's internal processes (Drucker 1997). Hardware and software development for data processing and dissemination, i.e., the transformation of data into useful and actionable market insights, significantly trails that of data generation, transmission and storage. Moreover, firms lack the ability to even use existing technology to generate information (Blattberg et al. 1994).

In sum, the potential of available data is tremendous, but firms' resources required to take full advantage of them are severely restricted. The technology gap between data generation and information generation is only one source of restriction. Firms' available management resources to generate and disseminate information and managers' cognitive resources to keep up with new market insights are also insufficient to cope with the data explosion. The information revolution is increasing the importance of allocating these limited resources to the "right" data.

2.2 Empirical Observations

There exist relatively little empirical insights into how firms cope with the flood of data, though not surprisingly, there is strong and persistent evidence that firms (i.e., managers) only pay selective attention to data about their business environment (e.g., Day and Nedungadi 1994; Deshpandé and Zaltman 1982). In marketing, firms are frequently criticized for overemphasizing internal information relative to external information. For example, a majority of the firms in Day and Nedungadi (1994) are classified as self-centered, since they pay little attention to external information to assess their competitive advantage. This is supposedly inferior to a market-driven approach which focuses on external information. "Reengineering" is blamed for inducing many firms to focus excessively on cost without creating much competitive advantage (Business Week 1996). Most applications of information technology cited for their success, such as airline reservation systems, supply and inventory management in retailing, or package tracking systems, are related to internal processes and much less to better understanding customer preferences or competitor behavior. Many managers admit that the most pressing need to achieve their firm's goals is to acquire more information about customers (Murray and Myers 1997).

A selective focus, which allows firms to learn more details, comes at the price of narrowing the field of vision (Day and Nedungadi 1994). The market orientation literature suggests that this price is typically too high (Day and Wensley 1988; Narver and Slater 1990). Most empirical research of information processing and utilization has focused on the antecedents of observed firm and management behavior (e.g., Deshpandé and Zaltman 1982; Moorman 1995). Evidence from studies that try to explain firm performance with information acquisition behavior is week or only indicates an association rather than a causal link (e.g., Glazer, Steckel and Winer 1992; Narver, Jacobson and Slater 1993; Thomas, Clark and Gioia 1993).

Is broad information necessarily better than detailed information? Eisenhardt (1989) examined strategic decision making in high-tech firms. She found that in slower paced industries managers considered fewer alternatives at greater depth than managers who operated in high-velocity environments. In other words, managers favored depth over breadth when faced with less uncertainty. Thus, the more appropriate question seems to be: *When* is breadth preferred over depth?

The increased rate of change in most business environments requires firms to constantly adapt. Drastic firm changes are typically explained with either discontinuous changes in its environment (e.g., deregulation) or a firm's past mistakes (e.g., IBM). More often than not, drastic changes are accompanied with new leadership with a completely different background (e.g., L. Gerstner at IBM). On the other hand, Emerson Electric is also undergoing a dramatic change. The champion of an internal cost focus is now aggressively searching for external growth opportunities (Fortune 1995). Yet, the company was hugely successful driving down cost, it still has the same CEO, and its environment has not significantly changed. How can we explain these changes?

In sum, we know that firms are selective in their acquisition of information, they have no other choice given their available resources. We suspect that they tend to be (too) narrow-sighted and to have a bias in favor of internal information. As a result they miss changes in the market place and must then drastically change their focus to “catch up.” Do a focused allocation of resources and drastic changes in their allocation generally imply that firms do not behave optimally?

2.3 Related Analytic Literature

Two streams of analytic research have emerged that examine the optimal acquisition of information by firms. One stream - adaptive control models - assumes that firms learn by observing market outcomes and examines how decisions (pricing, promotions, etc.) should be adjusted to optimize learning and future profits (e.g., Grossman et al. 1977; Harrington 1995; Little 1966). The second stream assumes that firms can acquire information (e.g., market forecasts) from a research firm before making a decision. This stream focuses on how much information firms should acquire under various market conditions (e.g., Hwang 1993; Li, McKelvey and Page 1987) and whether they should share private information with their competitors (e.g., Gal-Or 1985; Malueg and Tsutsui 1996; Vives 1984).[1] Both streams have only examined the acquisition of information about one uncertain factor and are thus silent about the tradeoffs for information about multiple factors.

Cyert, Kumar and Williams (1993) explored learning about external (customer preferences) *and* internal (cost) uncertainties as a source of firm rents. The paper focused on how learning changes over time in a dynamic model similar to those of the first stream. The authors concluded that learning about either uncertainty is a viable source of firm rents. From their results follows that firms should focus first on external data. Over time, internal data grow in relative importance and firms should gradually pay more attention to internal data. However, they did not examine the tradeoff between depth and breadth of information or the effect of firm and market characteristics.

We share the interest in the optimal acquisition of *both* external and internal information with Cyert et al. (1993), but assume that data are available from an exogenous source. We depart from game-theoretic models of the second stream in an important way. These models have assumed that data are costly and firms have unlimited resources to process them. In contrast, we assume that

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[1] Issues of information acquisition have also been addressed in the auction literature (e.g., Matthews 1984; Milgrom 1981) and the analyses of noisy rational expectations models of a financial market (e.g., Grossman and Stiglitz 1980; Verrecchia 1982).

data are free, but resources to process them are limited and insufficient to cope with all available data.[2] The optimal allocation of resources is not immediately obvious since the expected value of information depends on the expected impact of information on a firm's decision and not directly on the allocation of resources. Moreover, the competitor's allocation must also be considered.

3. The Model

The model developed in this section is a two-stage game with two identical quantity setting firms. The firms are risk neutral and maximize expected profit. In the first stage, firms generate private information. They do this by allocating their available data processing resources to available external data and to internal data. For convenience, we label these resources "management time." A firm can allocate its management time equally to external and internal data – a *balanced* allocation – or focus (more) on either demand or cost data – an *unbalanced* or *focused* allocation. In other words, firms must trade off breadth with depth of information. In the second stage, firms set the production level for their products using the acquired information. We determine the pure equilibrium strategies for the whole game and examine the effect of various firm and market factors. This setup is similar to the models by Li et al. (1987) or Hwang (1993), except that there is no monetary cost of information.

A priori, information is expected to yield higher expected profits through changes in decisions. We do not consider situations in which information itself is a product that can be sold at some price. Although this is a rapidly growing market (Sarvary and Parker 1997), most companies acquire information for problem-oriented or decision-making purposes (Murray and Myers 1997).

3.1 The Market Environment

Each firm produces and markets a single product in an uncertain environment described by a linear inverse demand function:

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[2] The view of information acquisition as an allocation of resource other than money is consistent with the description of information acquisition as attention (Bettman 1979; Kahneman 1973) or awareness (Rogers 1983).

$$p_i = a - b \cdot q_i - d \cdot q_j, \quad a > 0, \quad 0 \le d \le b, \tag{1}$$

and a linear marginal cost function:

$$m_i = c + e \cdot q_i, \quad c > 0, \quad e \ge 0, \quad i, j = 1, 2, i \ne j. \tag{2}$$

The firms determine output, q_i, and the market place determines the market clearing price, p_i. Profits are $\pi_i = (p_i - m_i)q_i$. The *degree of competition* is captured by the product substitutability, d. Competition is highest when the products are homogeneous, i.e., $d = b$, and lowest when they are independent, i.e., $d = 0$. While in marketing we often think of firms as competing on prices rather than quantities, Kreps and Scheinkman (1983) note that the outcome of the Cournot model is also the outcome when firms first choose capacities and then compete on a basis of price. Cournot models have relevance for many situations where firms make strategic decisions before pricing that can reduce price competition.

The firms' uncertainty about external market factors and internal firm factors is captured by uncertainty about demand and marginal cost. More specifically, the firms are concerned about *shifts* in demand and marginal cost, indicated by the parameters a and c, respectively. The demand parameter a indicates the market potential and the cost parameter c the level of costs for the firms' products. Uncertainty about the two parameters is capture by a continuous distribution, $g_1(\theta)$, with existing mean vector, $E[\theta] = [\mu_a \ \mu_c]^T$, and covariance matrix

$$V[\theta] = \begin{bmatrix} u & 0 \\ 0 & u \end{bmatrix}, \quad \text{where } \theta = \begin{bmatrix} a \\ c \end{bmatrix}. \tag{3}$$

$E[\theta]$ represents the firms' *prior beliefs* and variance u the level of *prior uncertainty*. This specification implies that (i) the firms are equally uncertain about demand and cost, and (ii) demand and marginal cost are independent. The distribution, $g_1(\theta)$, is common knowledge and all other parameters, i.e., b, d, and e, are assumed to be known to both firms.

3.2 The Generation of Information

The firms have access to costless data about the two uncertain parameters and management time, T, available to process these data.[3] The underlying premises of our paper are that (i) all available data are potentially useful, and (ii) the available amount always exceeds firms' management time, T, to process them. Thus, all management time will be used and T can be set to 1 without loss of generality.[4]

Information is generated from the data in the form of $x_i = \theta + \varepsilon_i$. The firms receive two signals, one about demand, x_{ai}, and one about cost, x_{ci}. Given the lack of sufficient management time, firms cannot obtain perfect information. The signals will always contain some error. The amount of error in each signal depends on the amount of allocated management time to process the data. The error, $\varepsilon_i = [\varepsilon_{ai}\ \varepsilon_{ci}]^T$, in the information, $x_i = [x_{ai}\ x_{ci}]^T$, is described by a continuous distribution, $g_2(\varepsilon_i)$, with existing mean vector, $E[\varepsilon_i] = 0$, and covariance matrix

$$V[\varepsilon_i] = \begin{bmatrix} \phi(t_i) & 0 \\ 0 & \phi(1-t_i) \end{bmatrix}, \quad i, j = 1, 2, i \neq j. \tag{4}$$

The variable, t_i, represents firm i's allocation of management time. More specifically, it indicates the fraction of management time allocated to demand data. The remaining fraction, $1-t_i$, is allocated to cost data. When $t_i = 0.5$, firm i allocates its management time equally to demand and cost data, respectively. In other words, it uses a balanced allocation. Otherwise, the allocation is unbalanced and the firm favors either demand or cost information. The information generation is not sequential and firms generate only one set of information, x_i, i =1, 2. The allocation of management time is made prior to seeing any information and cannot be changed retroactively.

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[3] Alternatively, T could be interpreted as an exogenous budget to acquire costly information.

[4] This implies that (i) firms cannot be overloaded with information and (ii) no strategic advantage of ignorance exists. In contrast, Gal-Or (1988) shows that a firm benefits from ignorance about cost when the error in the acquired information is related to the production level. In our model, the error in information does not depend on the subsequent (production) decision. Moreover, available resources could be shifted to demand data if cost data were less desired, and vice versa. An advantage of ignorance can also arise when one firm can learn from the other by observing decisions. However, we assume simultaneous decision making, which eliminates this strategic consideration.

The function $\phi(\tau)$ maps allocated management time, τ, into error, i.e., variance, of information. It is assumed continuous and twice differentiable in τ. More management time always reduces error, i.e., $\phi' < 0$, but at a diminishing rate, i.e., $\phi'' > 0$. In other words, generating more accurate information becomes more and more difficult.[5]

The function $\phi(\tau)$ also captures the effectiveness of the allocated resources, τ, in processing data. This effectiveness depends on a firm's processing ability (e.g., number and quality of managers, software to process data, etc.) and the quality or diagnosticity of available data. An increase in effectiveness shifts down $\phi(\tau)$ for any τ. The *effectiveness of management time*, η, is represented by the inverse of the lowest achievable error, $\phi(1) > 0$, when all available management time is allocated to the same data, i.e., $\eta = 1/\phi(1)$.

The information is assumed to be unbiased. Its error, ε_i, is assumed to be uncorrelated with the true parameter, θ, i.e., $\mathrm{Cov}[\theta\ \varepsilon_i] = 0$, as well as with the error in the competitor's information, ε_j, i.e., $\mathrm{Cov}[\varepsilon_i\ \varepsilon_j] = 0$. Moreover, as indicated in (4), the firm's individual signals are also assumed uncorrelated, conditional on θ, i.e., $\mathrm{Cov}[\varepsilon_{ai}\ \varepsilon_{ci}] = 0$.

The information is used to update the beliefs, $E[\theta]$, about demand and cost. The distributions, $g_1(\theta)$ and $g_2(\varepsilon_i)$, are such that the updating results in linear posterior expectations, i.e.,

$$E[a \mid x_i] = \mu_a + w_{ai}(x_{ai} - \mu_a) \quad \text{and} \quad E[c \mid x_i] = \mu_c + w_{ci}(x_{ci} - \mu_c),$$

$$\text{where} \quad w_{ai} = \frac{u}{u + \phi(t_i)} \quad \text{and} \quad w_{ci} = \frac{u}{u + \phi(1 - t_i)}. \tag{5}$$

In addition, the firms must anticipate the content of the competitor's private information:

$$E[x_{aj} \mid x_i] = E[a \mid x_i] \quad \text{and} \quad E[x_{cj} \mid x_i] = E[c \mid x_i], \quad i, j = 1, 2,\ i \neq j. \tag{6}$$

This distributional assumption holds for the exponential family of conjugate distributions, which includes the normal, beta-binomial, and gamma-Poisson processes (Ericson 1969). The last two are

[5] When the function exhibits increasing returns, i.e., $\phi'' < 0$, the results are trivial (see section 3.4).

especially appropriate for imposing non-negativity constraints on the uncertain parameters. This class of distributions has been frequently assumed in models with incomplete information. The updating process represents a weighing of existing knowledge, E[θ], and new information, x_i, where the (Bayesian) weights, w_{ai} and w_{ci}, are determined by the covariance between uncertain parameter and information, relative to the unconditional variance of information.

3.3 Equilibrium Output

The equilibrium concept we use is that of a *perfect Bayesian equilibrium* (Fudenberg and Tirole 1991). Moreover, we limit our analysis to pure equilibrium strategies. The equilibrium of the game is found by proceeding backwards in two steps. First, the unique Bayesian-Nash equilibrium of the second stage of the game, $q^* = (q_i^*, q_j^*)$, is determined for given allocations $t = (t_i, t_j)$. The first-stage decision, i.e., the equilibrium allocation of management time, $t^* = (t_i^*, t_j^*)$, i, j = 1, 2, i ≠ j, is then found by assuming that the profits from the first stage decisions are determined by equilibrium behavior in the second stage of the game. Both firms are expected to adhere to this strategy.

Given the common knowledge of the distributions $g_1(\theta)$ and $g_2(\varepsilon_i)$ and the allocation of management time, $t = (t_i, t_j)$, chosen by each firm in the first stage, firm i determines its output, q_i^*, in the second stage by maximizing expected profit, conditional on the information, x_i.

PROPOSITION 1. *For any allocation of management time, $t = (t_i, t_j)$, there is a unique Bayesian equilibrium to the second-stage game, which is linear in the information, x_i, i.e., $q_i^* = Q + K_{ai}(x_{ai} - \mu_a) + K_{ci}(x_{ci} - \mu_c)$, where for i, j = 1, 2, i ≠ j,*

$$Q = \frac{\mu_a - \mu_c}{2\beta + d}, \quad K_{ai} = w_{ai}\frac{2\beta - d \cdot w_{aj}}{\xi_a}, \quad \text{and} \quad K_{ci} = -w_{ci}\frac{2\beta - d \cdot w_{cj}}{\xi_c},$$

$$\text{with} \quad \xi_k = 4\beta^2 - d^2 w_{ai} w_{aj}, \ k = a, c \quad \text{and} \quad \beta = b + e. \tag{7}$$

PROOF: See Appendix A.

The equilibrium output, q_i*, is adjusted upward or downward from the ex-ante equilibrium quantity, Q, depending on the deviation of the information, x_i, from prior beliefs, E[θ]. The value of information is determined by the expected profit impact of expected changes in the output decision, q_i*, from Q. If a (risk neutral) firm does not expect information to change its decision, the information has no expected value. It is therefore important to understand how the model parameters affect the sensitivities, K_{ai} and K_{ci}, of the output decision to information.

First, the sensitivity, K_{ai}, to demand information depends on the weight, w_{aj}, the competitor gives to demand information, which in turn depends on the competitor's allocation of management time, t_j. The quantity adjustment is larger, the less management time the competitor allocates to demand data and thus, the noisier the resulting information. This follows directly from (7). If the error in competitor's demand information is low, the firm's new insights about demand are more likely to be known to the competitor and thus, less useful to gain an advantage. This is consistent with the finding that Cournot competitors do not want to share private information (Vives 1984).

Second, K_{ai} increases as the error in the demand information, $\phi(t_i)$, for a given t_i decreases or uncertainty, *u*, increases. In both cases the firm is more confident in the demand information, x_{ai}, relative to its prior belief, μ_a (see (5)). Error $\phi(t_i)$ decreases when management time is more effective, i.e., when data are easier to process, the firm has more management time available or can employ it more effectively (e.g., with more diagnostic data or a better decision support system).

Third, the more substitutable the products are, i.e., the higher *d*, the smaller the quantity adjustment. Competition limits the potential for quantity adjustments and thus, the expected value of information. For the same reason, the marginal effect of information decreases with both *b* and *e*. A steeper inverse demand function or marginal cost function leaves less "room" for quantity adjustments. To simplify the subsequent analysis, we define $\beta = b + e$ without loss of generality.

Finally, these insights also apply to the magnitude of the marginal effect of cost information, K_{ci}, though the quantity adjustment due to cost information, x_{ci}, is in the opposite direction ($K_{ci} < 0$). In other words, with higher expected demand firms increase production, with higher expected cost they reduce it.

3.4 Equilibrium Resource Allocation

3.4.1 Analytic Solutions. If identical firms follow their Bayesian output decisions (7) in the second stage of the game, the expected unconditional profit as a function of the firms' resource allocations, $t = (t_i, t_j)$, is:

$$E[\Pi_i(t)] = \beta(\Pi_0 + Z_i(t)), \quad \text{with}$$

$$\Pi_0 = Q^2 \quad \text{and} \quad Z_i(t) = K_{ai}^2\left(u + \phi(t_i)\right) + K_{ci}^2\left(u + \phi(1 - t_i)\right), \tag{8}$$

where Π_0 represents the expected profit without information and $Z_i(t)$ the expected value of information.[6] As discussed above, the expected value of information is higher, the more it is expected to change the firm's production decision, q_i*, i.e., the higher the sensitivity of the output decision to the acquired information. In fact, the expected value increases at an increasing rate as indicated by the quadratic terms, K_{ai}^2 and K_{ci}^2, respectively. The payoff function $Z_i(t)$ leads to the following first-order conditions of the game:

$$\frac{\partial Z_i(t)}{\partial t_i} = -K_{ai}^2 \frac{\zeta_a}{\xi_a}\phi'(t_i) + K_{ci}^2 \frac{\zeta_c}{\xi_c}\phi'(1 - t_i) = 0, \quad i = 1, 2, \tag{9}$$

where $\zeta_k = 4\beta^2 + d^2 w_{ki} w_{kj}$, k = a, c, and ξ_a and ξ_c are as defined in (7).

PROPOSITION 2. *For identical firms, any equilibrium allocation of management time, t_i* and t_j*, $i \neq j$, must lie on the linear line*

$$t_j^* = 1 - t_i^*. \tag{10}$$

PROOF: Given equilibrium output (7) and profit function (8), the payoff function, $Z_i(t)$, is symmetric. From this symmetry and the assumption that firms are identical follows that either $t_i^* = t_j^*$ or $t_i^* = 1 - t_j^*$. However, $Z_i(t_i, t_i) < Z_i(t_i, 1 - t_i)$, $\forall\, t_i \neq 0.5$, i = 1, 2. ■

[6] The result follows directly from $E[\Pi_i(t)] = \beta \cdot E_i[q_i^{*2}]$ and $E[q_i^{*2}] = E[q_i^*]^2 + V[q_i^*]$.

COROLLARY 3. *If a balanced allocation of management time is best for firm i, it is also best for firm j, i.e.,* $t_i^* = t_j^* = 0.5$. *If equilibrium allocations* $t_i^* \neq 0.5$, *i = 1, 2, exist, then identical duopolists allocate different amounts of management time to demand and cost data.*

Proposition 2 describes the potential equilibrium strategies of the game. Existence and uniqueness follow from the properties of the payoff and best response functions. The best response functions, $t_i = r_i(t_j)$, are monotone decreasing (see Appendix A). However, since the equilibrium line (10) is also decreasing, neither the existence of an interior equilibrium nor its uniqueness is ensured, since the best response curves could cross not at all or more than once. Moreover, the payoff function, $Z_i(t)$, is not necessarily concave with respect to t_i, $0 \leq t_i \leq 1$ (see Appendix A).

We first provide the condition for which the best response functions cross the equilibrium line (10) once and the payoff function, $Z_i(t)$, is concave. This condition coincides with the condition for a balanced allocation of management time.

PROPOSITION 4. *The necessary and sufficient condition for a balanced allocation of management time to generate information, i.e.,* $t_i^* = t_j^* = 0.5$, *to be the unique equilibrium of the game is*

$$\phi'' > \frac{2\phi'^2}{u+\phi} \cdot \frac{2\beta}{2\beta - dW} > 0, \quad i = 1, 2, \quad W = w_{ak}(t_k = 0.5) = w_{ck}(t_k = 0.5),\ k = i, j. \tag{11}$$

PROOF: See Appendix A.

Condition (11) indicates the degree of diminishing returns required for a balanced equilibrium allocation of management time. If the returns are non-diminishing, i.e., $\phi'' \leq 0$, the game has only corner solutions. This condition is more restrictive than the second-order conditions. In other words, $t_i = 0.5$ (i = 1, 2), can be a profit maximum, but not an equilibrium of the game. More specifically, though in such a case a balanced allocation is a Nash equilibrium, it is not stable or trembling hand perfect. A small deviation (tremble) from $t_i = 0.5$ leads to an unbalanced equilibrium allocation, $t_i \neq 0.5$ (i = 1, 2), at which both firms have higher expected profits.

PROPOSITION 5. *If condition (11) does not hold, the game has two identical symmetric equilibria at $t_i^* = 1 - t_j^* \neq 0.5$, i, j = 1, 2, $i \neq j$. The equilibrium allocation is unbalanced and determined by the first-order conditions (9) or is a corner solution.*

PROOF: See Appendix A.

3.4.2 Description of Equilibrium Allocations. The equilibrium allocations of the game can be separated into 3 cases (see Table 1 and Figure 1). First, as described in Proposition 4, when condition (11) holds, the unique equilibrium allocation of management time is balanced, i.e., $t_i^* = t_j^* = 0.5$ (case 0). As shown in Figure 1a, the payoff function, $Z_i(t)$, is nicely behaved.

There are two reasons for firms to deviate from a balanced allocation of management time. In case 2, a focused allocation of management time to either demand or cost data yields information of higher expected value than a balanced allocation. In case 1, the possibility of reducing competition by acquiring different information increases the value of a focused allocation over a balanced allocation. This effect is also present in case 2, but is secondary. The two cases do not differ in the equilibrium (see Proposition 5), but in the pattern of best response functions, $r_i(t_j)$, and the shape of the payoff function, $Z_i(t)$.

When the second-order conditions hold at $t_i = 0.5$, i = 1, 2, indicating a profit maximum, but condition (11) does not hold, the best response functions cross three times (Figure 1b). However as discussed earlier, the equilibrium at $t_i = 0.5$, i = 1, 2, is not stable. This leads to the two identical symmetric equilibrium allocations described in Proposition 5. When the second-order conditions do not hold at $t_i = 0.5$, i = 1, 2, the payoff function, $Z_i(t)$, has two identical maxima at $t_i \neq 0.5$, and $1-t_i$, for any t_j, or is convex for $0 \leq t_i \leq 1$. In the former situation, the best response function cross the equilibrium line (10) twice, at $t_i \neq 0.5$, and at $1-t_i$ (Figure 1c). In addition, the best response functions are discontinuous at $t_i = 0.5$, i = 1, 2.

Table 1 summarizes the effect of the model parameters on condition (11). Overall, the condition is more likely to hold, the higher uncertainty, *u*, the lower product substitutability, *d*, the lower effectiveness of management time, η, and the steeper the slopes of the inverse demand or the

Table 1

Summary of Equilibrium Allocation of Management Time

	Condition (11) holds	Condition (11) does not hold
Second-order conditions hold	**Case 0: $t_i^* = t_j^* = 0.5$** High uncertainty *u* Low effectiveness η Low competition *d* Steep slopes β	**Case 1: $t_i^* \neq 0.5$, $t_j^* = 1 - t_i^*$** Lower uncertainty *u* Higher effectiveness η Higher competition *d* Flatter slopes β
Second-order conditions do not hold	N/A	**Case 2: $t_i^* \neq 0.5$, $t_j^* = 1 - t_i^*$** Same trends as in Case 1, but larger changes required

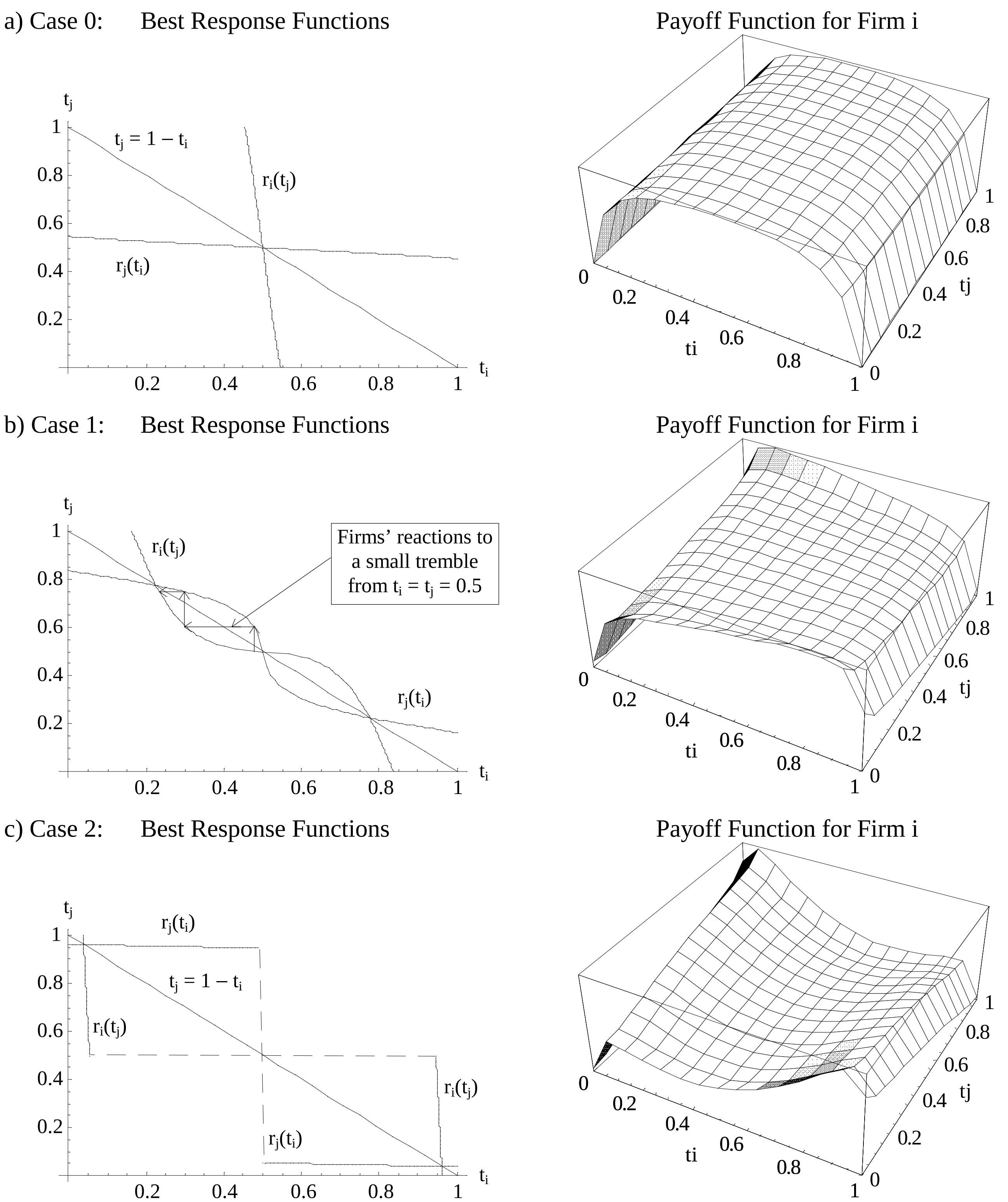
marginal cost functions (higher β). These effects also hold with respect to the second-order conditions. However, condition (11) is violated first, i.e., it cannot hold when the second-order conditions do not hold.

The existence of an interior equilibrium other than $t_i = t_j = 0.5$, also depends on the function ϕ. For example, with $\phi(\tau) = e^{s-r\tau}$ the only equilibrium allocations are $t_i^* = 0.5$, when condition (11) holds, and $t_i^* = 1 - t_j^* = 0, 1$, otherwise (i, j = 1, 2, i ≠ j). Equilibrium allocations change discontinuously as model parameters change. With $\phi(\tau) = s - r\tau^k$, $0 < k < 1$, $s > r$, interior solutions other than $t_i = t_j = 0.5$ exist. Both functional forms satisfy the assumptions about ϕ, but the relationship between ϕ′ and ϕ″ is different.

The existence of both balanced and unbalanced equilibrium allocations follows from (i) the effect of management time, τ, on the error of information, ϕ(τ), and (ii) the impact of the weight, w_{ai}, given to demand information (or w_{ci} to cost information) on the expected value of information. The first effect is a diminishing by assumption, i.e., $\phi'' > 0$. The second has an increasing effect on the expected value of information (see (5) and (8)). The total effect of a firm's resources to generate information on the expected value of information is a combination of these two effects. If the diminishing returns to management time dominate, the equilibrium allocation of management time is balanced. Otherwise it is unbalanced.

Figure 1

Best Response $r_i(t_j)$ and Payoff Functions $Z_i(t)$



*) This figure was created in Mathematica assuming $\phi(\tau) = s - r\tau^k$.

Table 2

Relationship Between Changes in Value of Information and Allocation of Resources

Increase in Parameter	Expected Value of Information	Equilibrium Resource Allocation
Uncertainty u	Increases	More Balanced
Effectiveness η	Increases	More Focused
Competition d	Decreases	More Focused
Slope Parameters β	Decreases	More Balanced

3.4.3 Comparative Statics. When the equilibrium allocation is balanced, i.e., $t_i^* = 0.5$, i = 1, 2, condition (11) yields insights about the effect of changes in the environment. When the equilibrium allocation is unbalanced, but an interior solution, such insights are obtained from the comparative statics results.

PROPOSITION 6. *The equilibrium allocation of management time is more balanced, the higher uncertainty (higher u), the steeper the inverse demand or the marginal cost function (higher β), the less effective management time (higher η), or the lower product substitutability (lower d). In other words,*

$$\frac{dt_i^*}{du},\ \frac{dt_i^*}{d\beta} > 0 \quad \text{iff } t_i^* < 0.5 \quad \text{and} \quad \frac{dt_i^*}{du},\ \frac{dt_i^*}{d\beta} < 0 \quad \text{iff } t_i^* > 0.5, \tag{12a}$$

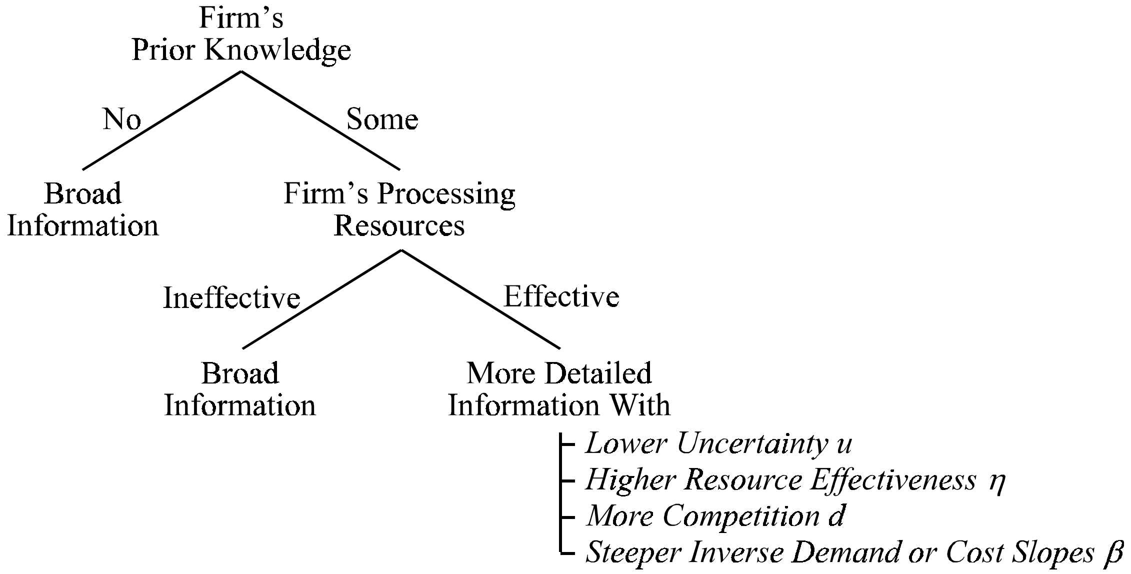
$$\frac{dt_i^*}{d\eta},\ \frac{dt_i^*}{dd} < 0 \quad \text{iff } t_i^* < 0.5 \quad \text{and} \quad \frac{dt_i^*}{d\eta},\ \frac{dt_i^*}{dd} > 0 \quad \text{iff } t_i^* > 0.5. \tag{12b}$$

PROOF: See Appendix A.

The comparative statics results correspond with condition (11) as summarized in Table 1. However, they do not directly correspond to the sensitivity of the output decision (7) to changes in the parameters (see discussion in §3.3). In other words, the changes in the equilibrium allocation are not driven by changes in the expected value of information alone. Therefore, one cannot make conclusions about firms' equilibrium information acquisition behavior from solely looking at

Figure 2

Optimal Allocation of Resources as a Function of Environment



changes in the expected value of information. The competitive interactions for the acquisition of information must also be taken into account. These differences are summarized in Table 2.

3.4.4 Interpretation of Results. We next discuss the implications of these analytic results for our widget manufacturer. These insights are also summarized in Figure 2.

The two most important determinants of the optimal resource allocation are the level of prior uncertainty, u, and the weight given to the information, x_i, relative to prior expectations, E[θ]. In fact in the case of a monopoly, these are the only parameters that matter. In other words, the optimal allocation does not depend on the slopes of the inverse demand and the marginal cost functions when the products are independent. This follows directly from Condition (11) and $d = 0$.

Without any prior knowledge, i.e., $u \to \infty$, the widget firm should always seek information about both demand and cost conditions, i.e., have a balanced allocation of management time. It makes sense that the widget firm should not expect to be competitive in its market when being completely ignorant about either demand or cost. The result that firms should favor broad over detailed information the higher the environmental uncertainty, is consistent with the empirical findings of management behavior reported in Eisenhardt (1989).

If the widget firm has some prior knowledge, but the information does not receive a lot of weight relative to prior knowledge, the optimal allocation remains balanced. For a given level of uncertainty, u, the weight is low when the effectiveness of management time, η, is low. In other words, when the widget firm has difficulty obtaining new insights to improve its decisions, it should prefer broad information about both demand and cost to detailed information about only one of the two.

In these first two environments the widget firm and its competitor should always have a balanced allocation. As a result, when uncertainty is high, data are not diagnostic, or firms have no or only ineffective resources to generate information, companies develop similar knowledge in equilibrium, all else equal.

This preference for broad information has implication for data sellers. First, customers, i.e., firms, have similar data needs, which offers less opportunity for market segmentation. Second, customers value detailed data about a few market factors less than broad data about many different factors. Thus, the data seller should invest in adding additional data products rather than in improving the quality of the data. It should also expect customers to spread its resources among different data sellers with different data products.

In other environments, i.e., when the widget firm has some prior knowledge and management time is (somewhat) effective, the optimal allocation of management time to external and internal data depends on the relative values of the parameters. In this situation, Proposition 6 provides the direction in which parameters push the equilibrium allocation (see also Figure 2). Corollary 3 states that in equilibrium when one firm focuses on demand data, the competitor focuses to the same degree on cost data. Thus, we should expect firms to develop different knowledge when uncertainty is limited, management time effective and competition high. In equilibrium, learning is a way for firms to differentiate themselves and to reduce competition. In these situations it is easier for data sellers to segment the market. Moreover, they are better off providing very detailed data about a limited number of factors, i.e., they should specialize.

The progression from case 0 to case 1 to case 2 as parameters continue to change can be linked to the product life cycle. Firms in new markets typically have little prior knowledge and available data, are less effective in processing the data, and competition is limited. Thus, they should favor broad information and allocate management time equally to both demand and cost data. In mature markets, prior knowledge is much better, firms are better able to process the larger amounts of data, and competition is more intense. Consequently, firms should favor depth of information and focus management time more on either demand or cost data. In other words, the optimal allocation should become more unbalanced over time as a market matures. This is a different conclusion than the findings by Cyert et al. (1993) indicate. However, their model starts with a different set of assumptions. One note of caution, this is a dynamic interpretation of the results from a static game. Nevertheless, our prediction still applies to different markets in different product life cycle stages.

Today's business environment is typically characterized as more uncertain and more competitive. At the same time, technology makes more and more data available. These trends have different effects on the optimal allocation of resources. Increasing uncertainty leads to more balanced allocations, increasing competition and the promise of better information to more focused allocations, all else equal. As a result, there is no simple rule of thumb how firms should allocate their resources to learn about the business environment.

4. Model Extensions and Limitations

The model developed in §3 is based on a number of simplifying assumptions. In this section we will present findings from relaxing three of them. First, we show the effect of correlation between the uncertain parameters on the equilibrium allocation of management time. Second, we relax the assumption that demand and cost conditions are the same with respect to uncertainty and the effectiveness of processing available data. Finally, we extend the model to a Cournot oligopoly. At the end of this section we briefly discuss potential limitations of our model. The mathematical details for the presented model extensions are available in Appendix B.

4.1 Correlated Parameters

In (3) we assume that the demand parameter, a, and cost parameter, c, are independent. There are a number of reasons why this may not be exactly true. For example, a successful firm is potentially able to influence both demand and cost through a superior strategy. Exogenous factors, like changes in economic conditions can also simultaneously shift demand and cost. For example, with inflation we would expect both the level of cost and the realized price for the firm's product to increase, i.e., a positive correlation. In wine production, excellent weather can increase consumer exceptions about the quality of the wine, which shifts demand outward, and reduce costs, since the high quality crop requires less work to eliminate bad grapes, i.e., a negative correlation. This example applies to many process improvements that simultaneously increase quality and decrease cost.

When the two parameters, a and c, are dependent, i.e., $\mathrm{Cov}(a\ c) = \rho_\theta u \neq 0$, inferences about demand can be made from cost information and vice versa, regardless whether the parameters are positively ($\rho_\theta > 0$) or negatively correlated ($\rho_\theta < 0$). Thus, a non-zero correlation ρ_θ should significantly influence a firm's allocation of management time to generate information. At first glance, it appears that a higher absolute correlation should lead to a more focused allocation. In the extreme case with $|\rho_\theta| = 1$, information about both demand and cost conditions can be obtained by focusing on either demand or cost data. In other words, we would expect the resulting equilibrium allocations to be more unbalanced than in the case with independent parameters.

The actual comparative statics result indicates that this intuition is not entirely correct. It only holds for situations with a negative correlation, i.e., $\rho_\theta < 0$. In situations with positively correlated parameters the allocation of management time becomes more and not less balanced:

$$\frac{\mathrm{d}t_i^*}{\mathrm{d}\rho_\theta} > 0 \quad \text{iff } t_i^* < 0.5 \text{ and } \rho_\theta < 1 \quad \text{and} \quad \frac{\mathrm{d}t_i^*}{\mathrm{d}\rho_\theta} < 0 \quad \text{iff } t_i^* > 0.5 \text{ and } \rho_\theta < 1 \qquad (13)$$

If the widget firm expects a process innovation to improve product quality and reduce production cost at the same time, i.e., a shift of demand and cost in opposite directions, it should focus its management time more on either demand or cost, all else equal. If it is concerned with inflationary tendencies, it should more balance its allocation, all else equal.

The reason for this result is that the inference effect described above is dominated by the market implication of the correlation, ρ_θ. Positively correlated parameters imply that any "discovered" demand increase is at least partly offset by a simultaneous cost increase, and any "discovered" cost decrease by a demand decrease. This limits the effect of information on the adjustments of quantity, q_i*. In fact when $\rho_\theta = 1$, no information is acquired at all. Information would only reduce the level of uncertainty of a firm's knowledge, but not affect the output decision, q_i*. A reduction in uncertainty about the optimal decision has no value to risk-neutral firms. In that sense, a high positive correlation, ρ_θ, represents another explanation for why firms do not expect to give information a lot of weight in the same way as non-diagnostic data or ineffective resources. As the parameters are less positively correlated, the firms' incentives to specialize and focus more on either demand or cost data increase.

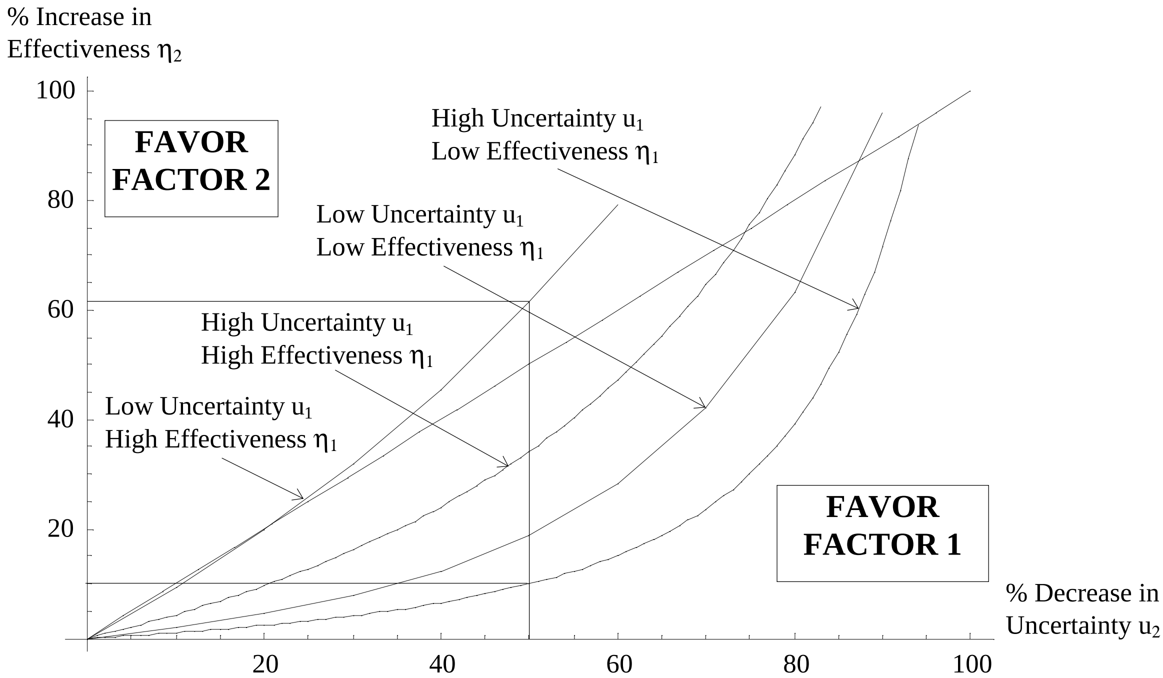
4.2 Differences Between Demand and Cost

In many situations, firms are more knowledgeable about internal factors, have access to better data about them and are better able to process these data. With the assumptions contained in (3) and (4), we have limited our analysis to situations when firms are equally uncertain and equally able to generate information about demand and cost, respectively. This allowed us to directly examine the tradeoff between broad and detailed information.

Relaxing these assumptions is straightforward and the results are rather intuitive. Firms should allocate more management time to the factor with higher uncertainty (u_a versus u_c) or higher effect of management time (η_a versus η_c), all else equal. (The subscript *a* relates to demand and *c* to cost.) However, when both parameters are different, the overall effect is not immediately obvious since decreases in prior uncertainty, *u*, and increases in effectiveness, η, have opposing effects. Figure 3 provides an indication of the relative sensitivities of the resource allocation to these two effects. The horizontal axis indicates the percent decrease in one uncertainty, i.e., $(u_1 - u_2)/u_1$. The

Figure 3*

Improvement of Processing Ability as a Function of Uncertainty Decreases



*) This figure was created in Mathematica assuming $\phi(\tau) = s - r\tau^k$.

curves then indicate the percent increase in the effectiveness of management time for the same data, i.e., $(\eta_2 - \eta_1)/\eta_2$, needed for the value of demand and cost information to be the same. The four curves represent four different environments as indicated in the figure. The straight line represents the points where a 1 percent decrease in uncertainty, u_2, corresponds to a one percent increase in processing ability, η_2. Changes in other model parameters, like competition, *d*, have only a marginal impact on the curves of Figure 3.

Figure 3 illustrates that in many cases the optimal allocation of management time is more sensitive to increases in the effectiveness of management time, η, than to reductions in uncertainty, *u*. Consequently, if a firm is more uncertain about demand, but better able to obtain cost information, the latter effect often dominates and we should expect firms to focus more on cost data. For example, with high demand uncertainty, u_a, and low effectiveness, η_a, in processing demand data, a fifty percent decrease in cost uncertainty, u_c, relative to demand uncertainty, u_a, requires about a ten percent increase in effectiveness of management time for cost data, η_c. If the increase in effectiveness is less than that, the firm should focus more on demand, i.e., remedy the higher uncertainty. If the increase is higher, the firm should focus more on cost, i.e., take advantage of the better processing ability. When uncertainty u_a is relatively low and effectiveness η_a, high, the "break-even point" increases to about sixty-two percent.

Asymmetry between demand and cost can also lead to discontinuous jumps in the optimal allocation of management time as the environment changes. For example, when it is optimal to focus on cost data, for example, because of higher effectiveness, η_c, a marginal increase in demand uncertainty, u_a, or effectiveness in processing demand data, η_a, can make a focus on demand data optimal. Such a jump occurs because the equilibrium allocation of management time does not necessarily move gradually towards demand data, but jumps discontinuously, due to the convexity in the payoff function (see Figure 1c). The allocation of management time on the curves in Figure 3 is not necessarily balanced. These curves only indicate the points where the firms are indifferent between demand and cost data.

4.3 Cournot Oligopoly

The third extension examines the impact of the entry of a third identical firm. How should it allocate its management time and how should the incumbent firms react? When condition (11) holds and the incumbent firms have a balanced allocation, i.e., case 0 in Table 1, then the entrant should pursue also favor broad information, i.e., $t_i^* = 0.5$ (i = 1...3). However, the incentive to deviate from a balanced allocation increases as the number of firms increases. This is consistent with the finding that increasing competition leads to more unbalanced equilibrium allocations.

When the incumbents have unbalanced allocations, i.e., cases 1 or 2 in Table 1, the entrant should match the allocation of either incumbent firm, i.e., $t_k^* = t_i^* = 1 - t_j^*$ (i, j, k = 1..3, i ≠ j ≠ k). The incumbents' allocations become more unbalanced to reflect the increase in competition and the expected profit of firm j is higher. The extension of this result to *n* firms is straightforward. With an even number of competitors, half the firms focus on demand data, the other half on cost data. With an odd number of competitors, the last firm focuses either on demand or cost data. Otherwise, all findings from the Cournot duopoly model continue to hold.

In sum, relaxing these three model assumptions provides interesting additional results. However, the general insights presented in §3 are not materially affected by these changes.

4.4 Model Limitations

Our model assumes that firms “pay” for information with the allocation of a fixed and given resource, management time. While it is true that data collection is not free, our assumption reflects the reality of many cases where the limiting factor to become better informed is not the cost of data, but a firm’s limited processing capacity. Managers must become informed about their business environment. Yet, a firm’s number of managers is limited and each manager has limited time. The incremental benefit of more managers is limited by coordination and information dissemination problems. If the acquisition of information is limited by the costly nature of data, firms do not have to trade off breadth with depth of information, unless there is an exogenous, binding budget constraint.

Though we do not explicitly include the cost of the resources in our model, our results can be used to examine the effect of changes in the cost of the resources. A cost decrease would lead a firm to increase its management time, η, which is equivalent to an increase in the effectiveness of management time. According to Proposition 6, this leads to a more focused allocation. Thus, corporate downsizing should lead to a preference for broader and less detailed information, all else equal.

Our model considers a simultaneous one-shot game. This is justified in many situations, like the one-shot decision to set the capacity of a new production plant. Most information is acquired for problem related purposes (Deshpandé and Zaltman 1982). Often the prior commitments to data collection and processing are very strong and require a long lead time. For example, clients of IRI or AC Nielsen have to order data well in advance. The development of computer software also takes time. Assuming a leader-follower structure for decision making adds interesting competitive interactions, since the leader has to take into account that its private information is “leaked” through its actions. Addressing this issue is left for future research.

The choice of parameters to model external and internal uncertainty provides another opportunity for future research. A preliminary analysis indicates that the results continue to hold with uncertain slope parameters. We also eliminated the need to learn about a competitor through the assumptions about common knowledge and the equilibrium concept. Alternatively, competitor decision making could be modeled through a reaction function with unknown parameters. Other possibilities include uncertainty about a competitor’s prior beliefs or ability to generate information, which can be researched with the help of available data.

For reasons of parsimony we concentrated our analysis on the allocation of resources to two uncertain factors. There is no obvious reason why the results regarding the tradeoff between depth and breadth of information should not continue to hold for more than two uncertain factors. Examining the same problem when firms are not identical provides additional opportunities for future research. Some preliminary results indicate that when firms have different levels of prior uncertainty, it is possible that they focus on the same data rather on different data.

Finally, some assumptions were imposed for reasons of mathematical tractability. For example, we assume that demand and marginal cost functions are linear. Functional form assumptions are never really convincing, although our assumptions are consistent with existing analytic research on information acquisition. It also allows for less restrictive assumptions about the distributions for prior knowledge and information acquisition. In addition, there is some research suggesting that comparative statics derived from simpler models often hold more generally (Milgrom 1994).

5. Concluding Remarks

This paper proposes a parsimonious game-theoretic model to examine a firm’s optimal resource allocation to acquire information. The model reflects the reality of many industries where the mass of available data exceeds a firm’s resources to process them. Existing analytic research in economics has primarily examined *how much* demand or cost information firms should acquire. Our model allows us to explicitly examine the *tradeoff between* demand and cost information and, more importantly, between broad and detailed information about uncertain factors. Or in the words of the Greek poet quoted at the beginning of our paper, we show when a firm should be a “hedgehog” and when a “fox.”

Our paper provides a number of insights that should be of value to academics studying questions of firm information acquisition and management and to data providers who want to better understand the needs and preferences of their clients. First, since the expected value of information depends on its expected impact on a firm’s decision and not directly on the allocation of resources, the optimal allocation depends on the business environment. Even without differences between demand and cost with respect to uncertainty, quality and availability of data, and processing ability, a firm may prefer to focus its resources to thoroughly understand a few uncertain factors and ignore data about other factors. Second, in this situation identical duopoly firms pursue different strategies with one focusing more on external data and the other more on internal data. Third, with higher degrees of competition, higher effectiveness of management time, or less uncertainty, a firm should increasingly prefer detailed information and thus focus its resources. Fourth, marginal changes in the environment can lead to discontinuous jumps in the optimal resource allocation.

These findings suggest that acquiring detailed information through a “narrow field of vision” is optimal provided a firm can substantially reduce its uncertainty about the targeted factors. Moreover, drastic changes in firm behavior with respect to allocating resources to learn are not always caused by insufficient changes or failures in the past or discontinuous jumps in the environment. They can indicate optimal firm behavior. For example, the dramatic shift in strategy by Emerson Electric from a cost focus to an emphasis of growth (Fortune 1995) could be the optimal reaction to minor changes in the environment.

The question ‘why are firms different?’ has received considerable attention in the strategy literature (Rumelt, Schendel and Teece 1994). Observed differences among firms are often explained with differences in resource endowments or core capabilities. One reason for developing different resources or capabilities is that, in equilibrium, identical firms may want to learn about different uncertain factors of their business environment.

Finally, in the previous we raised a number of interesting research questions that can be addressed with the help of our framework. Beyond these theoretical issues there is the potential for empirical research to test our predictions.

Appendix A

Proof of Proposition 1

Expected profit for the second-stage quantity decision is:

$$\mathrm{E_i}\left[\pi_i \middle| \mathrm{x_i}\right] = \mathrm{E_i}\left[a - c - d \cdot \mathrm{q_j} \middle| \mathrm{x_i}\right] \cdot \mathrm{q_i} - \beta \cdot \mathrm{q_i^2}, \quad \text{i, j = 1, 2, i} \neq \text{j}. \tag{A.1}$$

Using the first-order condition, $\partial \mathrm{E_i}\pi_i/\partial \mathrm{q_i} = 0$, the quantity decision is:

$$\mathrm{q_i}^* = \frac{\mu_\mathrm{a} + \mathrm{w_{ai}}(\mathrm{x_{ai}} - \mu_\mathrm{a}) - \mu_\mathrm{c} - \mathrm{w_{ci}}(\mathrm{x_{ci}} - \mu_\mathrm{c}) - \mathrm{d} \cdot \mathrm{E_i}\left[\mathrm{q_j}^* \middle| \mathrm{x_i}\right]}{2\beta}. \tag{A.2}$$

In equilibrium, firm j is expected to adhere to the decision rule of Proposition 1. From (6) follows

$$\mathrm{E_i}\left[\mathrm{q_j}^* \middle| \mathrm{x_i}\right] = \mathrm{E_i}\left[\mathrm{Q} + \mathrm{K_{aj}}(\mathrm{x_{aj}} - \mu_\mathrm{a}) + \mathrm{K_{cj}}(\mathrm{x_{cj}} - \mu_\mathrm{c}) \middle| \mathrm{x_i}\right] = \mathrm{Q} + \mathrm{K_{aj}w_{ai}}(\mathrm{x_{ai}} - \mu_\mathrm{a}) + \mathrm{K_{cj}w_{ci}}(\mathrm{x_{ci}} - \mu_\mathrm{c}),$$

which results in the following five equations for i, j = 1, 2, i ≠ j:

$$\mathrm{Q} = \frac{\mu_a - \mu_c - d \cdot \mathrm{Q}}{2\beta}, \quad \mathrm{K_{ai}} = \mathrm{w_{ai}} \frac{1 - d \cdot \mathrm{K_{aj}}}{2\beta} \quad \text{and} \quad \mathrm{K_{ci}} = -\mathrm{w_{ci}} \frac{1 + d \cdot \mathrm{K_{cj}}}{2\beta}. \tag{A.3}$$

Proposition 1 follows immediately by solving these equations. ■

Second-Order Conditions

$$\frac{\partial^2 \mathrm{Z_i}(t)}{\partial t_i^2} = \frac{\mathrm{K_{ai}^2}}{\xi_a^2}\left[\frac{8\beta^2 \phi'(t_i^*)^2}{u + \phi(t_i^*)}\left(\zeta_a + d^2 \mathrm{w_{ai}w_{aj}}\right) - \xi_a \zeta_a \phi''(t_i^*)\right]$$
$$+ \frac{\mathrm{K_{ci}^2}}{\xi_c^2}\left[\frac{8\beta^2 \phi'(1 - t_i^*)^2}{u + \phi(1 - t_i^*)}\left(\zeta_c + d^2 \mathrm{w_{ci}w_{cj}}\right) - \xi_c \zeta_c \phi''(1 - t_i^*)\right] < 0. \tag{A.4}$$

From (A.4) follows immediately that $\phi'' > 0$ is necessary for any interior solution, i.e., $0 < t_i < 1$. As a result, the payoff function, $\mathrm{Z_i}(t)$, is not necessarily concave for all parameter values.

Best Response Functions

The slope of the best response functions $\mathrm{r_i}(t_j)$, i, j = 1, 2, i ≠ j follows from the cross partial derivatives, i.e.,

$$\frac{\partial^2 Z_i(t)}{\partial t_i \partial t_j} = -\frac{K_{ai}}{\xi_a^3} 4\beta d w_{ai} w_{aj} \frac{\phi'(t_i)\phi'(t_j)}{u+\phi(t_j)}\left[8\beta^2(\beta - d w_{ai}) + d^2 w_{ai} w_{aj}(4\beta - d w_{ai})\right]$$

$$+\frac{K_{ci}}{\xi_c^3} 4\beta d w_{ci} w_{cj} \frac{\phi'(1-t_i)\phi'(1-t_j)}{u+\phi(1-t_j)}\left[8\beta^2(\beta - d w_{ci}) + d^2 w_{ci} w_{cj}(4\beta - d w_{ci})\right] < 0. \qquad \text{(A.5)}$$

The two brackets of (A.5) are always positive and the two leading factors always negative. The second factor is negative because $K_{ci} < 0$ (see (7)). Thus, the slope of the best response functions is always negative for $t_i \neq 0.5$, i = 1, 2. ■

Proof of Proposition 4

A sufficient and (almost) necessary condition for the equilibrium allocation, $t_i^* = 0.5$, i = 1, 2, to be locally stable is (Varian 1992):

$$\begin{vmatrix} \frac{\partial^2 Z_i(t)}{\partial t_i^2} & \frac{\partial^2 Z_i(t)}{\partial t_i \partial t_j} \\ \frac{\partial^2 Z_j(t)}{\partial t_j \partial t_i} & \frac{\partial^2 Z_j(t)}{\partial t_j^2} \end{vmatrix} > 0 . \qquad \text{(A.6)}$$

Due to the symmetry of the payoff function, $Z_i(t)$, at $t_i = 0.5$ (i = 1, 2), this simplifies to $\partial^2 Z_i(t)/\partial t_i^2 - \partial^2 Z_i(t)/\partial t_i \partial t_j < 0$. Condition (11) follows immediately. Moreover,

$$\frac{\text{Condition (11)}}{\partial^2 Z_i(t)/\partial t_i^2} = \frac{(4\beta^2 + d^2 W^2)(2\beta + dW)}{4\beta(2\beta^2 + d^2 W^2)} > 1 \quad \text{for } d > 0,$$

where $W = w_{ak}(t_k = 0.5) = w_{ck}(t_k = 0.5)$, k = i, j. Hence, the condition for ϕ'' from the second-order conditions (A.4) is less restrictive and the payoff function, $Z_i(t)$, is bounded and concave when condition (11) holds. This together with the fact that the best response functions, $t_i = r_i(t_j)$, are monotone decreasing ensures existence and uniqueness of the equilibrium, $t_i^* = 0.5$, i = 1, 2 (Huang and Li 1990). ■

Proof of Proposition 5

First, any equilibrium at $t_i = 0.5$, i = 1, 2, cannot be stable when condition (11) is violated. The reaction function for firm i is flatter than the reaction function for firm j at $t_i = 0.5$ (see Figure 1c).

Second, the best response functions, $t_i = \mathrm{r_i}(t_j)$, can cross the equilibrium line (10) at most once for $0 < t_i < 0.5$ or $0.5 < t_i < 1$. This follows from the payoff function, $\mathrm{Z_i}(t)$, which consists of two additive parts, namely the expected value of demand information and the expected value of cost information (see (8)).

The expected value of demand information for $0 \le t_i \le 1$ increases (i) at a decreasing rate, (ii) first at a decreasing rate and then at an increasing rate or (iii) at an increasing rate. Correspondingly, the expected value of cost information decreases with t_i (i) at an increasing rate, (ii) first at an increasing rate and then at a decreasing rate, or (iii) at a decreasing rate. Case (i) leads to a balanced allocation (Proposition 4), since the sum of two concave payoff functions is again concave. Case (iii) only has corner solutions, since the payoff function, $\mathrm{Z_i}(t)$, is the sum of two convex functions and thus convex. Case (ii) allows for the possibility of higher expected profits for $t_i \neq 0.5$ even when $t_i = 0.5$ is a maximum. However for any given t_j, the payoff function, $\mathrm{Z_i}(t)$, can have at most one maximum for $t_i < 0.5$ (and one for $1-t_i > 0.5$ due to the symmetry of $\mathrm{Z_i}(t)$), since the second derivative of the payoff function for demand (cost) information changes its sign at most once. In other words, the payoff function, $\mathrm{Z_i}(t)$, is quasi-concave for $0 \le t_i < 0.5$ and for $0.5 < t_i \le 1$. If the best response function, $\mathrm{r_i}(t_j)$, does not cross the equilibrium line (10) for any $t_i \neq 0.5$, the game has only corner solutions, i.e., $t_i^* = 1-t_j^* = 0, 1$, i, j = 1, 2, i ≠ j. ■

Proof of Proposition 6

Since the proof of the effect of changes in η, d, β is similar, we present only the proof for the effect of u. The overall effect of changes in uncertainty, u, follows from

$$\left[\frac{\partial^2 \mathrm{Z_i}(t)}{\partial t_i^2} + \frac{\partial^2 \mathrm{Z_i}(t)}{\partial t_i \partial t_j}\frac{\partial t_j^*}{\partial t_i}\right]\frac{\mathrm{d}t_i}{\mathrm{d}u} + \left[\frac{\partial^2 \mathrm{Z_i}(t)}{\partial t_i \partial u} + \frac{\partial^2 \mathrm{Z_i}(t)}{\partial t_i \partial t_j}\frac{\partial t_j^*}{\partial u}\right] = 0\,. \tag{A.7}$$

From the stability condition (A.6) and $\partial t_j^*/\partial t_i = -1$ (see (10)) follows that the first bracket is always negative. The sign of the total effect of a change in uncertainty u, $\mathrm{d}t_i/\mathrm{d}u$, is determined by the sign of the second bracket. The sign of $\partial^2 Z_i(t)/\partial t_i \partial t_j$ is negative (see A.5). The sign of the first part of the second bracket is determined by

$$\frac{\partial^2 Z_i(t)}{\partial t_i \partial u} = -\frac{K_{ai}\phi'(t_i)}{\xi_a^2}\left[2\xi_a\zeta_a \frac{\partial K_{ai}}{\partial u} + 8\beta^2 d^2 K_{ai}\left(w_{ai}\frac{\partial w_{aj}}{\partial u} + w_{aj}\frac{\partial w_{ai}}{\partial u}\right)\right]$$
$$+\frac{K_{ci}\phi'(1-t_i)}{\xi_c^2}\left[2\xi_c\zeta_c \frac{\partial K_{ci}}{\partial u} + 8\beta^2 d^2 K_{ci}\left(w_{ci}\frac{\partial w_{cj}}{\partial u} + w_{cj}\frac{\partial w_{ci}}{\partial u}\right)\right]. \qquad \text{(A.8)}$$

When $t_i = t_j = 0.5$, the two parts are identical and $\partial^2 Z_i(t)/\partial t_i \partial u = 0$. The first part is positive and of larger magnitude when $t_i^* < 0.5$. The second part is negative and of larger magnitude when $t_i^* > 0.5$. Thus, $\partial^2 Z_i(t)/\partial t_i \partial u > 0$ when $t_i^* < 0.5$ and $\partial^2 Z_i(t)/\partial t_i \partial u < 0$ when $t_i^* > 0.5$. The sign for $\partial t_j^*/\partial u$ is found similarly. However, from Proposition 2 follows that when $t_i^* < 0.5$, then $t_j^* > 0.5$. In other words, in equilibrium when $\partial^2 Z_i(t)/\partial t_i \partial u > 0$, then $\partial t_j^*/\partial u < 0$, and vice versa. As a result, both parts of the second bracket of (A.7) are positive when $t_i^* < 0.5$, negative when $t_i^* > 0.5$, and zero when $t_i^* = 0.5$, yielding the result presented in Proposition 6. In sum, as uncertainty, u, increases, the equilibrium allocations, t_i^*, i = 1, 2, become more balanced. ■

References

Bettman, James R. (1979), *An Information Processing Theory of Consumer Choice*. Reading, MA: Addison Wesley.

Blattberg, Robert C. and Rashi Glazer (1994), "Marketing in the Information Revolution," in *The Marketing Information Revolution* (R. C. Blattberg, R. Glazer and J. D. C. Little, Eds.), Boston, MA: HBS Press, 9–29.

———, ——— and John D. C. Little (1994), *The Marketing Information Revolution*. Boston. MA: HBS Press.

Business Week (1996), "Strategic Planning," August 26, 1996, 46–52.

Cyert, Richard M., Praveen Kumar and Jeffrey R. Williams (1993), "Information, Market Imperfections and Strategy," *Strategic Management Journal*, 14 (Special Issue), 47–58.

Day, George S. and Prakash Nedungadi (1994), "Managerial Representations of Competitive Advantage," *Journal of Marketing*, 58 (April), 31–44.

Deshpandé, Rohit and Gerald Zaltman (1982), "Factors Affecting the Use of Market Research Information: A Path Analysis," *Journal of Marketing Research*, 19 (February), 14–31.

Drucker, Peter F. (1997), "The Future That Has Already Happened," *Harvard Business Review*, September-October, 20–24.

Eisenhardt, Kathleen (1989), "Making Fast Strategic Decisions in High-Velocity Environments," *Academy of Management Journal*, 32, 543–576.

Ericson, William A. (1969), "A Note on the Posterior Mean of a Population Mean," *Journal of the Royal Statistical Society*, 31 (2), 332–334.

Fortune (1993), "Dinosaurs?" May 3, 1993, 36–42.

——— (1995), "Growing Your Company: Five Ways To Do It Right," November 25, 1995, 32–38.

Fudenberg Drew and Jean Tirole (1991), *Game Theory*. Cambridge, MA: MIT Press.

Gal-Or, Esther (1985), "Information Sharing in Oligopoly," *Econometrica*, 53 (March), 329–343.

——— (1988), "The Advantages of Imprecise Information," *RAND Journal of Economics*, 19 (Summer), 266–275.

Glazer, Rashi, Joel Steckel and Russell Winer (1992), "Locally Rational Decision Making: The Distracting Effect of Information on Managerial Performance," *Management Science*, 38 (February), 212–226.

Grossman, Sanford J., Richard E. Kihlstrom and Leonard J. Mirman (1977), “A Bayesian Approach to the Production of Information and Learning By Doing,” *Review of Economic Studies*, 44 (3), 533–547.

——— and Joseph E. Stiglitz (1980), “On the Impossibility of Informationally Efficient Markets,” *American Economic Review*, 70, 393–408.

Harrington, Joseph E. Jr., “Experimentation and Learning in a Differentiated-Products Duopoly,” *Journal of Economic Theory*, 66, 275–288.

Huang, Chi-Fu and Lode Li (1990), “Continuous Time Stopping Games With Monotone Reward Structures,” *Mathematics of Operations Research*, 15 (August), 496–507.

Hwang, Hae-Shin (1993), “Optimal Information Acquisition for Heterogeneous Duopoly Firms,” *Journal of Economic Theory*, 59, 385–402.

Information Week (1994), “????”, (May 23, 1994).

Kahneman, Daniel (1973), *Attention and Effort.* Englewood Cliffs, NJ: Prentice Hall.

Kelly, Paul J. (1994), “Still Waiting for the Information Age,” *Marketing News*, 28 (12), 4–5.

Kreps, David and John Scheinkman (1983), “Quantity Precommitment and Bertrand Competition Yield Cournot Outcomes,” *Bell Journal of Economics*, 14, 326–337.

Li, Lode, Richard D. McKelvey and Talbot Page (1987), “Optimal Research for Cournot Oligopolists,” *Journal of Economic Theory,* 42, 140–166.

Little, John D. C. (1966), “A Model of Adaptive Control of Promotional Spending,” *Operations Research* 14 (November-December), 1075–1097.

Machlup, F. and Una Mansfield (1983), *The Study of Information: Interdisciplinary Messages.* New York, NY: John Wiley & Sons, Inc.

Malueg, David A. and Shunichi O. Tsutsui (1996), “Duopoly Information Exchange: The Case of Uncertain Slope,” *Journal of Industrial Organization*, 14 (1), 119–136.

Matthews, Steven (1984), “Information Acquisition in Discriminatory Auctions,” in *Bayesian Models in Economic Theory* (Marcel Boyer and Richard E. Kihlstrom, Eds.), Amsterdam, NL: Elsevier, 181–207.

McCann, John H. and John P. Gallagher (1990), *Expert Systems for Scanner Data Environments: The Marketing Workbench Laboratory Experience*. Boston, MA: Kluwer Academic Publishers.

Milgrom, Paul (1981), “Rational Expectations, Information Acquisition, and Competitive Bidding,” *Econometrica*, 49, 921–943.

——— (1994), "Comparing Optima: Do Simplifying Assumptions Affect Conclusions?" *Journal of Political Economy*, 102 (3), 607–615.

Moorman, Christine (1995), "Organizational Market Information Processes: Cultural Antecedents and Product Outcomes," *Journal of Marketing Research*, 32 (August), 318–335.

Murray, Peter and Andrew Myers (1997), "The Facts About Knowledge," *Information Strategy*, 1 (September), 29–33.

Narver, John C. and Stanley F. Slater (1990), "The Effect of a Market Orientation on Business Profitability," *Journal of Marketing*, 54 (October), 20–35.

———, Robert Jacobson and Stanley F. Slater (1993), "Market Orientation and Business Performance: An Analysis of Panel Data," Cambridge, MA: Marketing Science Institute, Report 93-121.

Rogers, Everett M. (1983), *Diffusion of Innovations.* New York, NY: The Free Press.

Rumelt, Richard P., Dan E. Schendel and David J. Teece (1994), *Fundamental Issues in Strategy*. Boston, MA: HBS.

Sarvary, Miklos and Philip M. Parker (1997), "Marketing Information: A Competitive Analysis," *Marketing Science*, 16 (1), 24–38.

Simon, Herbert A. (1957), *Models of a Man.* New York, NY: John Wiley & Sons, Inc.

——— (1993), "Strategy and Organizational Evolution," *Strategic Management Journal*, 14, 131–142.

Thomas, James B., Shawn M. Clark and Dennis A. Gioia (1993), "Strategic Sensemaking and Organizational Performance: Linkages Among Scanning, Interpretation, Action and Outcomes," *Academy of Management Journal*, 36 (April), 239–270.

Varian, Hal R. (1992), *Microeconomic Analysis.* New York, NY: W.W. Norton (5th edition).

Verrecchia, Richard E. (1982), "Information Acquisition in a Noisy Rational Expectations Economy," *Econometrica*, 50, 1415–1430.

Vives, Xavier (1984), "Duopoly Information Equilibrium: Cournot and Bertrand," *Journal of Economic Theory*, 34, 71–94.

Abstract

Information is of increasing importance to firms, but they lack resources and time to process all available data into information useful for decision making. This paper examines firms' optimal resource allocation to acquire information using a game-theoretic model of firms that face cost and demand uncertainty. The optimal resource allocation to acquire information about the two uncertain factors requires two kinds of tradeoffs. First, firms must decide whether cost or demand information is more valuable for decision making. Second, they must decide whether detailed information about one of them is more valuable than broad information about both of them. A better understanding of what data firms should process is important for helping them to better manage their information assets and for studying actual firm behavior. Moreover, insights about "customer behavior" are of great value to data sellers.

The main finding of this paper is that often *firms should prefer detailed information to broad information, in particular when uncertainty is limited, competition is high, and firms' effectiveness in processing available data into information is high.* Preferring depth over breadth of information is optimal even without differences between demand and cost with respect to uncertainty or effectiveness in processing data. In equilibrium, when one firm focuses its resources on data about external demand conditions, a second identical firm always focuses on data about internal cost conditions. In other words, firms use learning to differentiate themselves.