Misperceiving Interactions Among Complements and Substitutes: Organizational Consequences

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Systems composed of activity choices that interact in nonsimple ways can allow firms to create and sustain a competitive advantage. However, in complex systems, decision makers may not always have a precise understanding of the exact strength of the interaction between activities. Likewise, incentive and accounting systems may lead decision makers to ignore or misperceive interactions. This paper studies formally the consequences of misperceiving interaction effects between activity choices. Our results suggest that misperceptions with respect to complements are more costly than with respect to substitutes. As a result, firms should optimally invest more to gather information about interactions among complementary activities—e.g., concerning network effects—than about interactions among substitute activities. Similarly, the use of division-based incentive schemes appears to be more advisable for divisions whose products are substitutes than for divisions that produce complements. It is further shown that system fragility is not necessarily positively correlated with the strength of the interaction between choices. While systems of complements become increasingly fragile as the strength of interaction increases, systems of substitutes can become increasingly stable.
(*Interactions; Systems of Activities; Complementarities; Misperceptions; Substitutes; Organizational Design; Supermodularity; Fragility; Complexity; Division-Based Incentives*)

1. Introduction

In recent years, the topic of interaction among activity choices of firms has received a burst of attention in the organization, economics, and management literatures (e.g., Levinthal 1997, Milgrom and Roberts 1990, Porter 1996). In particular, it has been argued that systems of tightly interconnected activities play an important role in creating and sustaining a competitive advantage (Milgrom and Roberts 1995, Rivkin 2000). In contrast to these positive views of tight interconnectedness, another stream of literature has analyzed the potential downside of tight linkages, in particular in the context of changing environmental conditions (Levinthal 1997, Siggelkow 2001). In this paper, we add a new dimension to the analysis of tightly coupled systems. We study the relative costs of misperceiving interaction effects among choices that interact with each other in different ways. We use the term "misperception" very broadly, including any behavior that does not take into account the true interaction between two decisions. Such misperceptions can arise from various sources. For instance, a firm's incentive system may lead decision makers to neglect or undervalue externalities they impose on other decision makers in the firm. Similarly, in complex systems, boundedly rational decision makers (Simon 1957) are not likely to have a precise understanding of all interaction effects among the decisions

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they are engaged in. As a result, decision makers may ignore interaction effects, may over- or underestimate them, or have some uncertainty about their true value.

We set out to study for which types of interactions these misperceptions are likely to generate large performance declines. The answer to this question points to those situations in which a reduction of misperceptions of interaction effects is particularly valuable. While prior treatments of interaction effects have discussed interactions generically, or have concentrated solely on complementarities, this paper focuses on the distinction between complementary interactions and interactions of substitutes. Two activities are said to interact as substitutes if the marginal benefit of each activity decreases in the level of the other activity. Two activities interact as complements if the marginal benefit of each activity increases in the level of the other activity. Consider, for instance, the investment decisions by pure Internet retailers and by brick-and-click operators. A number of pure Internet retailers, most strikingly Amazon.com, have made large investments to add more product categories to their offerings. These investment decisions were generally driven by a belief that these investments were strongly complementary to each other. A larger number of product categories would increase the number of customers who would be attracted to the site; as a result, the marginal benefit of adding a new category would be increasing in the number of other categories that were offered. As Jeffrey Bezos, Amazon.com's CEO, noted in Amazon's Annual Report in 1999: "As we expand our offering, we create a virtuous cycle for the whole business."

In contrast, consider the problem of how much to invest in different distribution channels—a problem faced, e.g., by Barnes & Noble, which sells books through superstores (Barnes & Noble), mall stores (B. Dalton), and the Internet (barnesandnoble.com). Especially in a market that is not growing fast,[1] investments in different outlets operated by the same firm tend to be substitutes. The more convenient it is to buy through one channel, the smaller the marginal benefit of increasing the convenience of buying through another channel. Thus, both Amazon.com and Barnes & Noble faced investment problems composed of interdependent investment decisions. In both cases, the optimal investment levels depended on the strength of the interaction effect between the investments. However, in both cases the true degree of interaction was not known—both firms had to use their best estimates of the expected interaction effect between their investments, and likely, both firms did not chance upon the true interaction effect: They had a degree of misperception. For which firm were misperceptions likely to be more detrimental?

The results of our analysis suggest that misperceptions of complementary interactions tend to be more detrimental than misperceptions of substitute interactions. Over- and underestimating complements can be very costly, whereas over- or underestimating substitutes tends to be less detrimental. The costs of misperceiving substitutes tend to be smaller because the underlying payoff relationship is in part self-correcting. For instance, brick-and-click operators may have underestimated the degree of substitution between channels, yet the overinvestment in one channel tended to be partially balanced by an underinvestment (relative to optimal) of other channels through which they were selling as well. In contrast, with overestimated complements, overinvestments in one area lead to further overinvestments in other areas, since marginal benefits are increasing in the levels of investment. In such situations, investment levels can easily spin out of control, far away from optimal levels. (For a fuller discussion of the underlying dynamics, see §4.1.)

In sum, interactions between complements behave quite differently from interactions between substitutes. As a result, it tends to be optimal for firms to invest more to garner information about interaction effects—i.e., to reduce the degree of misperception—when activities interact as complements than when they interact as substitutes. Similarly, if keeping activities within an organizational unit helps to reduce misperceptions of interaction effects, complementary activities should be left together, while activities that

[1] According to U.S. Census data, the growth rate of book retailing has been flat, if not declining, since Internet selling has become available. The compounded annual growth rate of book retailing was 8.87% for the period 1992–1997, and 8.14% between 1997–2001.

interact as substitutes may be placed in different organizational units or firms.

The rest of the paper is structured as follows: In the following section, we summarize previous findings from the managerial and organizational literature that relate to the topic of misperceiving interactions and the consequences that can arise from these misperceptions. Section 3 briefly discusses related theoretical approaches to this topic and contrasts our setup with prior work. Section 4 contains the main analysis. Section 5 discusses a number of organizational implications of the results and concludes.

2. Sources of Misperception

The concept of interactions among a firm's activities has a long heritage in the organizational literature (e.g., Galbraith 1977, March and Simon 1958, Thompson 1967). In particular, the research on organizational configurations (e.g., Khandwalla 1973, Miller and Friesen 1984) and activity systems (e.g., Porter 1996, Siggelkow 2002) has documented the high degree of interconnectedness among a firm's activity choices. While misperceptions of interaction effects have not been studied systematically, the organizational literature points to a number of potential sources for misperceptions and provides examples of the consequences of misperceiving interactions. We will briefly lay out two potential sources of misperceptions—outdated managerial models and parochial incentive systems—and describe the reported consequences.

2.1. Outdated Managerial Models

Because interactions among activities are pervasive within organizations, a number of interactions are internalized by managers and organizations in the form of heuristics and organizational routines (Nelson and Winter 1982), e.g., "if spending on design technology increases by 10%, investments on manufacturing technology should be increased by 10% as well." At the same time, managerial mental models that reflect these heuristics and underlying interactions are slow to adapt (Hambrick and Mason 1984, Kiesler and Sproull 1982, Murmann and Tushman 1997). As a result, when underlying interaction patterns change, mental models and their associated heuristics can become outdated, leading to interactions that are ignored or misperceived. The incidence and consequences of such misperceptions have been documented in various settings.

In the context of technological innovation, Henderson and Clark (1990) and Henderson (1993) show how firms with deeply ingrained organizational routines have a difficult time responding to shifts in knowledge that relate to new ways in which parts of a system (a product or a production process) interact with each other, i.e., to changes in interaction effects. Similar findings have been reported by studies that document the struggles encountered by U.S. firms that adopted lean manufacturing practices. In their attempts to replicate lean manufacturing, many managers failed to recognize that the value of individual practices was greatly affected by the presence of other practices, i.e., that practices interacted (Hayes and Jaikumar 1988). For instance, the value of flexible manufacturing systems was greatly enhanced by concurrent investment in worker education and a broadening of the product line, yet originally many U.S. firms were apparently not aware of these interaction effects and ignored them, consequently changing their existing system only in an incremental fashion, leading to detrimental outcomes (Jaikumar 1986).

A detailed example of ignored interaction effects can be found in Siggelkow (2001), who provides a historical account of Liz Claiborne, a fashion apparel manufacturer. Over the 1980s, Liz Claiborne had constructed an intricate system of interconnected choices that had allowed the company to create great shareholder value. Part of this system was a choice not to offer to its retailers the possibility of reordering items. This choice allowed Liz Claiborne to have no production-to-order, to have low spending on information systems and distribution, to deal with a large number of small suppliers based in the Far East which yielded long lead times, and to design six collections per year (rather than the typical four). These choices were complementary to each other in the sense that each choice increased the marginal benefit of other choices (Milgrom and Roberts 1990).[2]

[2] For instance, the value of production-to-order is generally higher when a firm offers reordering than when it does not. Conversely,

In the early 1990s, Liz Claiborne started a reordering program for its retail customers. However, Liz Claiborne's management changed only one element of this system: It allowed department store buyers to reorder individual items and promised to deliver within two weeks. Existing management ignored the interactions between the no-reorder policy and its other activity choices, leading to a large inventory build-up and consequent write-offs that had a large impact on Liz Claiborne's profitability. Only a new management team that had expertise with lean reordering systems was able to take these interactions into account and engaged in a number of changes, including partial production-to-order, increased spending on information technology, shift of suppliers to the Western Hemisphere with shorter lead times, and a reduction to four design cycles.

In sum, as these examples illustrate, one source of misperception of interactions are managers' mental maps of existing interaction patterns that do not adjust as rapidly as required by changes in the true underlying relationships.

2.2. Division-Based Incentive Systems

Misperceptions can also arise from incentive systems that do not take externalities of actions fully into account. For instance, many firms have created profit centers inside the corporation (Reece and Cool 1978) and have tied managers' compensation to their profit centers' performance (Dearden 1987). On the one hand, this simplifies a manager's decision process, since consequences of actions beyond her division can be ignored. On the other hand, by focusing on division performance rather than on firm performance, externalities are ignored, leading to actions that might be suboptimal from the firm's overall perspective. Related problems can arise from cost accounting systems that decompose costs linearly while the true costs are interdependent (Banker and Atkinson 1996).

While the direct consequences of inducing misperceptions through incentive systems have not been studied empirically in a systematic way, two studies have investigated the relationship between the degree of firm-level incentives (which would tend to reduce "misperceptions") and the degree of interactions among divisions within a firm. Both Bushman et al. (1996) and Keating (1997) find that the higher the degree of interdependence between divisions of a firm, the higher the degree of firm-level incentives. While these findings are consistent with the results of the formal analysis in this paper, these studies do not distinguish between different types of interactions. As a result, they do not shed light on the question of whether division-based incentives are used (or should be used) more aggressively in firms in which investments in different divisions interact as substitutes (say in divisions that produce substitute products), or in firms in which divisions' investments interact as complements.

Similar to the work by Bushman et al. (1996), research on the concept of "loose coupling" (Glassman 1973, Orton and Weick 1990, Weick 1976, 1982) has focused only on the intensity of interaction rather than on different types of interactions. In loosely coupled systems the interdependence between activities is low, while in tightly coupled systems the interdependence is high. While this literature does not address the question of misperceptions directly, some indirect indications of the consequences of errors are provided. For instance, Orton and Weick (1990) note that loose coupling is associated with stability and resistance to change—and presumably to mistakes—because in loosely coupled systems, changes in one part of the system do not propagate to other parts. Conversely, in systems with tight coupling, changes (and errors) tend to spread quickly (Firestone 1985, Wilson and Corbett 1983).

In sum, the organizational literature provides evidence that (a) choices within firms interact, (b) decision makers may misperceive or ignore these interactions, and (c) these misperceptions have organizational performance consequences. However, the question for which types of interactions misperceptions matter most has not been studied systematically. In the next section, we provide a brief preview of the model that we use to address this question and discuss related theoretical work.

the cost of a reordering program is lower when the firm is able to produce to order (Hammond 1993).

3. Preview of Model and Related Theoretic Approaches

To study the effects of misperceptions for different types of interactions, we set up a simple yet flexible model that allows for both substitutes and complements and includes a parameter determining the strength and nature of the interaction between the choices. In the model, managers have to choose the levels of two interconnected activities A and B to maximize an objective function $V = f(A, B, \alpha)$, where α is an exogenous parameter determining the interaction between A and B. Managers misperceive the true interaction parameter α to be z. For instance, if $z = 0$ while $\alpha \neq 0$, managers are said to ignore the interaction. This misperception leads to a performance decline as compared to no misperception. The objective function is assumed to be quadratic, $V = A + B + \alpha AB - A^2 - B^2$. Thus, if α is positive, A and B are complements; if α is negative, A and B are substitutes. In sum, we study the costs of misperceptions as a function of α.

Because the costs of misperceptions are equivalent to the benefits that are obtained when misperceptions are reduced, our analysis is conceptually related to prior work studying the value of signals that carry information about unknown parameters. (In our case, we address the question under which conditions a more precise estimate of the unknown interaction parameter α is most valuable, i.e., the conditions under which a firm might want to invest more to get a better signal or estimate of α.) The general setup in this literature is as follows: Assume a decision maker's payoff f depends both on her real-valued action x and the state of the world θ; i.e., $f(x, \theta)$. The agent considers θ to be a realization of a random variable Θ. Moreover, θ is not observable. However, the decision maker observes the realization of a signal z, which is also a random variable and which carries some information about the true realization of θ. Blackwell (1951, 1953) derives the conditions that determine when one signal is more valuable (in an expected sense) than another signal for *any* decision problem. These conditions (statistical sufficiency) turn out to be very restrictive, leading various authors to restrict the set of decision problems under consideration in order to derive broader conclusions. For instance, Jewitt (1989) restricts f to be concave, while Lehman (1988) focuses on monotone decision problems. A decision problem is monotone if observing a higher signal realization induces a higher action. Athey and Levin (2000) continue the study of monotone decision problems by considering general sets of payoff functions that are alike in how the incremental returns to higher actions change with θ, e.g., the set of supermodular payoff functions. Athey and Levin's work is particularly related to the present study because the quadratic function analyzed in our model is supermodular for positive values of the interaction parameter α.[3]

Athey and Levin (2000) are concerned with two problems. First, following Blackwell (1951, 1953) and Lehman (1988), they derive conditions under which for all agents within a family of decision makers, observing a signal z' is more valuable than observing z. Second, they provide conditions under which the incentives of two agents to acquire better information can be ranked. For instance, they show that a monopolist will acquire less information on uncertain marginal cost than a social planner would. Encompassing a wider range of payoff functions, Athey and Levin's work also extends the work of Persico (2000), who similarly studies for what conditions on f information about θ is more valuable.

As outlined above, the model studied in this paper also has the form of a decision maker choosing optimal levels $\mathbf{x}^*$ to maximize a function $f(\mathbf{x}, \alpha)$. Similar to the work described in the last paragraph, it is assumed that the decision maker does not observe the exogenous parameter α, but a signal z. The key conceptual difference to previous work is that in our model the value of α determines whether f is supermodular with respect to the actions $\mathbf{x}$, or not. (For this reason, we refer to this parameter as α rather than as θ.) We break supermodularity by considering a choice vector $\mathbf{x}$ that is more than one dimensional and by allowing the parameter α to affect the

[3] More generally, Topkis (1978) proves that a function $f(\mathbf{x})$ is supermodular if $\partial f^2/\partial x_i \partial x_j \geq 0$ for all $x_i \neq x_j$. For more details on supermodularity and the monotone comparative statics consequences resulting from supermodularity, see, for instance, Milgrom and Roberts (1990), Milgrom and Shannon (1994), Shannon (1995), and Athey (2002).

interaction between the components of $\mathbf{x}$. In §§4.1 and 4.2 we treat the case of a fixed parameter α, perceived with either a fixed or random error. In §4.3, we analyze the case in which the decision maker assumes that both the interaction parameter α and the signal z are realizations of random variables, thus mirroring the general setup of the literature described above. Last, in §4.4, the decision vector $\mathbf{x}$ is split between two managers who may have correlated or independent misperceptions.

Because the parameter α determines the type of interaction between the choices $\mathbf{x}$, our setup is not a special case of the models studied by Athey and Levin (2000) or Persico (2000). At the same time, though, in contrast to the more general treatments of Athey and Levin (2000) and Persico (2000), this paper confines itself to a single functional form. While a more general functional setup would clearly be preferable, the existing analytical structure of supermodular functions is not easily transferred to the present setting because the main emphasis of our study is to compare situations in which supermodularity holds to situations in which it does not. Consequently, as a first attempt to formally analyze the effects of misperceiving different types of interactions, we chose to focus on a particular functional form that has a long tradition in the literature, e.g., in the theory of teams (Groves and Radner 1972, Marschak and Radner 1972, Radner 1972), in models of organizational hierarchies (Geanakoplos and Milgrom 1991), organizational coordination (Crémer 1990, 1993), design partitioning (Schaefer 1999), and worker matching (Kremer 1993, Kremer and Maskin 1996).

4. Model and Analysis

4.1. Costs of Misperception and System Fragility

To study formally the effects of misperceiving interactions, a precise definition of *interactions* and the *strength* of interactions is needed. We chose to adopt a definition that has been previously used in the literature on teams (Marschak and Radner 1972) and is very consonant with the work on complementarities (Milgrom and Roberts 1990, 1992). Let V be a benefit function with arguments A and B. Then A and B are said to *interact* if the level of A affects the marginal benefit of B, and vice versa. The interaction between A and B is defined to be *stronger* than the interaction between C and D if the level of A affects in absolute value the marginal benefit of B more than the level of C affects the marginal benefit of D, and vice versa. Thus, if V is a twice-differentiable function, A and B are said to interact if $\partial^2 V/\partial A \partial B \neq 0$. A and B are complements if this cross-partial derivative is positive; they are substitutes if the derivative is negative. The interaction between A and B is stronger than the interaction between C and D if $|\partial^2 V/\partial A \partial B| > |\partial^2 V/\partial C \partial D|$. A and B are independent if this cross-partial derivative is zero. The basic model contains two activities A and B and one manager M1. The degree of interaction between A and B is measured by the parameter α.

Misperceptions of interactions have not been modeled previously in a direct manner, hence the literature does not provide much guidance in this regard. As a natural starting point, we focus on two different misperception structures: additive and multiplicative misperception. In the additive case, M1 misperceives the interaction between A and B to be $(\alpha + \delta)$ rather than α. For instance, if the interaction between two activities changed, one could think of $(\alpha + \delta)$ as the old interaction, and $-\delta$ as a change that M1 did not recognize. In the multiplicative case, M1 perceives the interaction to be $(1+\delta)\alpha$. Most of the results that are presented below hold for either form of misperception. Consequently, for the sake of exposition, we will focus on the additive case and note in the text when results differ.

To evaluate the effects of misperception, the case of no misperception—i.e., $\delta = 0$—is taken as a benchmark. Let $A^*(\alpha, 0)$ and $B^*(\alpha, 0)$ be the choices of A and B that maximize the benefit function V and denote with $V^*(\alpha, 0)$ the ensuing optimal performance. If M1 misperceives the interaction between A and B, M1 chooses activity levels $A^*(\alpha, \delta)$ and $B^*(\alpha, \delta)$, which will generally differ from $A^*(\alpha, 0)$ and $B^*(\alpha, 0)$. Let $V^*(\alpha, \delta)$ denote the ensuing payoff if the misperception is δ. A measure of the performance decline due to misperception is given by $R(\alpha, \delta) = V^*(\alpha, \delta) - V^*(\alpha, 0)$.

The final part of the model is the specification of the benefit function V. Let the benefit of choosing A and B be given by

$$V = A + B + \alpha AB - A^2 - B^2, \quad (1)$$

where the terms $-A^2$ and $-B^2$ can be thought of as the costs of choosing the levels A and B. Note $\partial^2 V/\partial A \partial B = \alpha$. In words, the larger $|\alpha|$ is, the more the level of A affects the marginal benefit of B and vice versa. Thus, $|\alpha|$ measures the strength of the interaction between A and B. The sign of α determines the nature of the relationship between A and B: A and B are complements if $\alpha > 0$, and substitutes if $\alpha < 0$.[4] Since M1 perceives the interaction to be $(\alpha + \delta)$, M1 chooses A and B to maximize:

$$V^1 = A + B + (\alpha + \delta)AB - A^2 - B^2.$$

Straightforward calculation yields that M1's choices are given by

$$A^*(\alpha, \delta) = B^*(\alpha, \delta) = \frac{1}{2 - \alpha - \delta}.$$

Substituting these choices into the true value function (1) and subtracting $V^*(\alpha, 0)$ yields

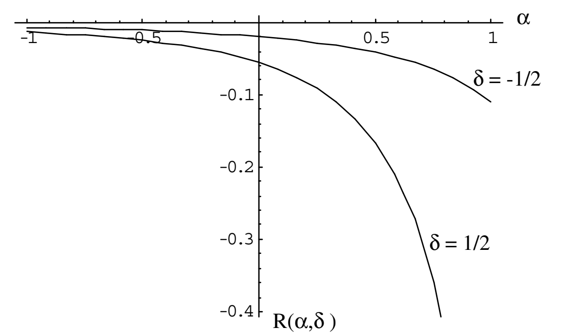
$$R(\alpha, \delta) = \frac{-\delta^2}{(2 - \alpha - \delta)^2 (2 - \alpha)}.$$

Figure 1 depicts $R(\alpha, \delta)$ for two values of δ. This simple figure is helpful in illustrating the following propositions. (For proofs of all propositions see the appendix.)

Proposition 1a. *Given functional assumption* (1), *for any given misperception modeled additively or multiplicatively, it is less costly to misperceive substitutes than to misperceive* (*equally strong*) *complements*.

Proposition 1a is illustrated in Figure 1 by picking a pair of symmetric interactions, $\alpha' > 0$ and $-\alpha' < 0$, and noting that the performance shortfall for $\alpha' > 0$ is larger than the performance shortfall for the corresponding $-\alpha' < 0$.

Figure 1 **Performance Shortfall** $R(\alpha, \delta)$ **for the Additive Case of Misperception**



The intuition behind Proposition 1a is that complements tend to amplify the consequences of misperceptions, while substitutes dampen them. For ease of exposition, we will think of A and B as investment levels and start with no misperception ($\delta = 0$). A positive δ increases M1's assessment of the marginal benefit of A given the current level of B, and increases M1's assessment of the marginal benefit of B given the current level of A, leading to (first-order) overinvestments in A and B relative to no misperception. Similarly, if δ is negative, M1 underinvests in A and B. Since A and B influence each other's marginal benefit, an additional second-order effect exists. In the case of complements, a higher level of A further increases the perceived benefit of B, leading to a further increase in B. In the same way, the higher level of B triggers an optimal upward adjustment of A, etc., until the perceived benefits of A and B equal their marginal costs. A similar argument applies for negative misperceptions ($\delta < 0$). In this case, M1's underinvestment in A triggers a further underinvestment in B, etc. Thus, with complements both first- and second-order effects pull A and B in the same direction away from their optimal values.

In contrast, when A and B are substitutes the second-order effects have a dampening effect. If δ is positive, M1 perceives the marginal benefit of A and B to be higher and overinvests. In this case, the higher level of A *decreases* the marginal benefit of B and leads to a reduction in B. Thus, the overinvestment in B is reduced. Similarly, the higher level of B decreases the

[4] To avoid confusion resulting from possible relabeling of choice variables, activities are labeled such that their marginal benefit increases in α. In the current setup, this is equivalent to assuming that A and B are defined such that they are positive numbers, which is a natural restriction for investment or effort levels.

marginal benefit of A and leads to a reduction in A. (Smaller third-order effects then work in the opposite direction, etc.) Thus, for substitutes, first- and second-order effects work in opposite directions, resulting in a dampening of the consequences of misperceptions. As this argument highlights, second-order effects play a crucial role in the result. Hence, it is important to note that the results derived in this paper may not be directly transferable to different setups in which second-order effects are less well-behaved due to discontinuities in the underlying functional form.

Given the definition of R, Proposition 1a can be interpreted alternatively as, "It is more beneficial to eliminate misperceptions for complements than for equally strong substitutes." This proposition can be generalized for any reduction in misperception:

Proposition 1b. *Given functional assumption* (1), *any reduction in misperception leads to a larger benefit for complements than for equally strong substitutes*.[5]

While Proposition 1a considered fixed degrees of misperception, the next proposition extends the results to a randomly distributed δ. Let $h(\delta)$ be the probability density function of δ with $E(h(\delta)) = 0$. The manager is thus assumed to perceive the true interaction effect with some degree of noise. Moreover, assume the manager can choose the variance of δ at cost $c(\mathrm{var}(\delta))$, with $c' < 0$, and $c'' > 0$; i.e., decreasing the variance is increasingly costly. Proposition 2 establishes that a firm that is maximizing expected benefits will invest more to reduce misperceptions—i.e., invest more to achieve a lower variance of δ—in the case of complements than in the case of equally strong substitutes (see the proof in the appendix for mild constraints on $h(\delta)$).[6]

[5] Also note that it is always beneficial to reduce misperceptions. Thus, signal $z = (\alpha + \delta_1)$ is preferred to signal $z' = (\alpha + \delta_2)$ if $|\delta_1| < |\delta_2|$ (see Proof of Proposition 1b in the Appendix).

[6] Note the expectation of the benefits is, in a sense, over a family of managers, each receiving a random draw δ_i, and thus having the misperception $(\alpha + \delta_i)$. The interaction parameter α is still a fixed number. Section 4.3 treats the more complex case in which α is also randomly distributed and the manager herself, when making her investment choices, is taking an expectation using the conditional distribution of α given her signal z.

Proposition 2. *Given functional form* (1), *if misperceptions are randomly distributed with mean zero, the expected marginal benefit of decreasing the variance of misperceptions is higher for complements than for equally strong substitutes. As a result, firms facing a complementary decision problem optimally invest more to reduce uncertainty around the interaction effect than firms that face a problem with equally strong substitutes*.

Consider, for instance, the use of cross-functional teams. Propositions 1b and 2 suggest that the value of cross-functional teams, which arguably can decrease the amount of misperception that exists in a given decision context, should be larger when the interactions between the functional departments that are present in the team have a complementary character rather than a substitute character. Moreover, the model suggests an increasing use of cross-functional teams, for instance, within product development when interactions are pervasive. As Hustad (1996) reports, firms are indeed using cross-functional teams significantly more often with projects that can be classified as "new to the world" or "new to the firm" than when the project is only a "minor improvement." On the level of the firm, Ruekert and Walker (1987) similarly find that more organic and participative coordination structures are used as the interdependence of marketing and other functional departments within a firm increases.

System Fragility. Many previous discussions of interaction effects have implicitly assumed that stronger interactions always lead to increased system fragility. Yet as Figure 1 shows, this need not always be the case.

Proposition 3a. *For a given misperception, stronger interactions do not always lead to higher performance declines*.

Note that while for $\alpha > 0$ the performance decline increases as $|\alpha|$ increases, the performance decline actually decreases for $\alpha < 0$ as $|\alpha|$ increases. Thus in this case, for substitutes, the stronger the interaction, the smaller the performance decline given a fixed amount of misperception. In other words, as interactions become stronger, a system can become more robust rather than more fragile.

It is important to note that the monotonically decreasing relationship between α and the performance decline (as depicted in Figure 1) does not always hold. It hinges on the absence of a "bliss point" with respect to misperceptions. If there exists a value α' for which misperceptions do not matter, i.e., for which the performance decline is zero regardless of misperception, then the performance declines at $(\alpha'+\varepsilon)$ and $(\alpha'-\varepsilon)$, for some small positive ε, have to be nonzero. In other words, the relationship between α and the performance decline cannot be monotonic (but has a local maximum at α'). For instance, in the case of multiplicative misperceptions, the monotonic relationship is broken because for $\alpha'=0$, misperceptions do not matter. A weaker statement, however, still applies to both the additive and the multiplicative case:

Proposition 3b. *Given functional assumption* (1), *a given misperception causes a larger increase in the performance decline when complements become stronger than when substitutes become stronger*.

4.2. Ignoring, Under-, and Overestimating Interactions

In this section, we first analyze the consequences of ignoring interaction effects, a presumably common type of misperception. In the additive model, ignoring interactions corresponds to a misperception equal to the negative of the true interaction, i.e., $\delta=-\alpha$ (such that $\alpha+\delta=0$), while in the multiplicative model it corresponds to $\delta=-1$ (such that $(1+\delta)\alpha=0$). Because results for both misperception structures are qualitatively similar, we continue to focus on the additive case.

We compare whether ignoring complements is more or less costly than ignoring equally strong substitutes. Formally, $R(\alpha,-\alpha)$, the performance decline due to ignoring complements, is compared to $R(-\alpha,\alpha)$, the performance decline due to ignoring substitutes, for all $\alpha>0$. (Recall the first argument of $R(\cdot)$ denotes the strength of the interaction; the second argument denotes the misperception.)

Proposition 4. *Given functional assumption* (1), *ignoring substitutes is less costly than ignoring* (*equally strong*) *complements*.

Ignoring interactions is a specific form of underestimating interactions (interactions are underestimated to the degree that they are ignored). The analysis can be extended to more general underestimations. We will concentrate on relationship-conserving underestimations, that is, underestimations for which the manager still perceives substitutes as substitutes and complements as complements. Thus, $R(\alpha,-\delta)$ is compared to $R(-\alpha,\delta)$ with $\alpha>0, \delta>0$, and $\alpha>\delta$. The last inequality states that the misperception is not strong enough to switch the true nature of the interaction.

Proposition 5. *Given functional assumption* (1), *underestimating complements, while still perceiving them as complements, is more costly than underestimating equally strong substitutes*.

Last, the consequences of overestimating complements are compared to the consequences of overestimating substitutes. Again, symmetric pairs of strengths of interaction and misperception are compared to each other.

Proposition 6. *Given functional assumption* (1), *overestimating complements is more costly than equally overestimating equally strong substitutes*.

4.3. Stochastic Interactions

In this section, we analyze misperceptions of the true interaction parameter when the interaction parameter itself is assumed to be randomly distributed. Consider a manager who receives a noisy signal z of the interaction parameter α, both of which she regards as random variables. Denote with $g(\alpha|z)$ the conditional distribution of α given signal z. To be more specific, assume that the manager's prior belief about α is that α is uniformly distributed over $[0,1]$ in the case of complements and $[-1,0]$ in the case of substitutes. Further assume that the manager receives a signal $z=\alpha+\delta$, with δ independently and uniformly distributed over $[-d,d]$. The manager thus maximizes over her choices $\mathbf{x}$,

$$E(V(\alpha|z))=\int f(x,\alpha)g(\alpha|z)\,d\alpha.$$

The resulting optimal choices $\mathbf{x}^*$ are a function of the signal z and the distribution parameter d. Further assume that the firm can invest in reducing the level of signal uncertainty. In particular, the firm can choose the level d at a cost $c(d)$, with $c' < 0$ and $c'' > 0$. Let $h(z)$ be the probability distribution function of z. Given optimal choices $\mathbf{x}^*$, the expected net benefit of choosing uncertainty level d is then given by:

$$E(V^*(d)) = \iint f(\mathbf{x}^*(z, d), \alpha) g(\alpha|z) h(z)\, d\alpha\, dz - c(d).$$

Using a quadratic production function as previously, a similar result to Proposition 2 can be shown:

PROPOSITION 7. *A firm will optimally invest more to reduce uncertainty about the strength of interaction between two activities, i.e., will choose a lower variance of the signal, when the activities interact as complements than when the activities interact as substitutes.*

4.4. Misperceptions with Two Managers

While the discussion in the previous sections was couched in terms of one manager, an equivalent setup with two managers exists. Manager M1 chooses the level of A, and manager M2 chooses the level of B. All of the above one-manager models are equivalent to this two-manager setup if both managers have the same misperception. Thus, both managers believe that the interaction is $(\alpha+\delta)$ rather than α. In the following, this assumption is relaxed and the two managers are allowed to have different misperceptions, $(\alpha+\delta_1)$ and $(\alpha+\delta_2)$.

With two managers, the true benefit function is still given by (1). M1, who chooses A, maximizes, however:

$$V^1 = A + B + (\alpha+\delta_1)AB - A^2 - B^2, \tag{2}$$

while M2, who chooses B, maximizes:

$$V^2 = A + B + (\alpha+\delta_2)AB - A^2 - B^2. \tag{3}$$

The Nash-equilibrium choices of M1 and M2 are then given by:[7]

$$A^* = \frac{2+\alpha+\delta_1}{4-(\alpha+\delta_1)(\alpha+\delta_2)}$$

and

$$B^* = \frac{2+\alpha+\delta_2}{4-(\alpha+\delta_1)(\alpha+\delta_2)}.$$

Given these choices, the resulting outcome is $V^*(\alpha, \delta_1, \delta_2)$ and the performance decline is defined accordingly as: $R(\alpha, \delta_1, \delta_2) = V^*(\alpha, \delta_1, \delta_2) - V^*(\alpha, 0, 0)$.

Stochastic, Independent Misperceptions. Assume that δ_1 and δ_2 are independently distributed with probability distribution functions $f(\delta_1)$ and $g(\delta_2)$. The expected performance decline is then given by:

$$E(R(\alpha, \delta_1, \delta_2)) = \iint R(\alpha, \delta_1, \delta_2) f(\delta_1) g(\delta_2)\, d\delta_1\, d\delta_2.$$

As shown in the appendix, the key results of the one-manager case continue to hold:

PROPOSITION 8. *Given functional assumption* (1), *with two managers who have randomly distributed misperceptions*:

(a) *in expectation, it is less costly to misperceive substitutes than to misperceive equally strong complements*

(b) *stronger interactions do not always lead to higher performance declines.*

Independent Versus Perfectly Correlated Misperceptions. An interesting question to raise is whether independent misperceptions are more costly than perfectly correlated misperceptions. In our setup, perfectly correlated misperceptions arise when the two managers hold the same belief about the interaction. Two studies have analyzed this question. First, Milgrom and Roberts (1995) show that if the elements of a function f are complements and random errors $\varepsilon_1, \ldots, \varepsilon_n$ are independently and identically distributed, then $E[f(x_1+\varepsilon_1, \ldots, x_n+\varepsilon_n)] \le E[f(x_1+\varepsilon_1, \ldots, x_n+\varepsilon_1)]$. In words, "when complementarities are present, 'fit' is important, that is, even mistaken variations from a plan are less costly when they are coordinated than when they are made independently" (p. 186). (For an extension of the result, see Schaefer 1999.[8]) Note, in

[7] In solving for the Nash equilibrium, it is assumed that each manager's belief about the other manager's perceptions are correct, i.e., that M1 believes that M2 perceives the interaction to be $(\alpha+\delta_2)$ and that M2 believes that M1 perceives $(\alpha+\delta_1)$.

[8] The Milgrom and Roberts (1995) finding requires that the shocks are either equal or independently distributed. By using a quadratic functional form, Schaefer (1999) generalizes this finding to cases where shocks are more highly correlated on one side of the above inequality than on the other.

Milgrom and Roberts' setup, errors occur directly on the choice variables and not on the perception of the interaction effect.

Second, Crémer (1990, 1993) studies the value of independent versus equal misperceptions using a setup that has a close resemblance to the model analyzed in this paper. Two managers independently chose A and B, respectively, resulting in the payoff:

$$V = \theta(A+B) + (\alpha-\beta)AB - \tfrac{1}{2}(\alpha+\beta)(A^2+B^2).$$

In contrast to our setup, in Crémer's model the interaction terms α and β are known. However, uncertainty exists around θ, the parameter on the linear terms, with each manager receiving a signal $\mu = \theta + \varepsilon$, where ε is randomly distributed. Crémer (1990, 1993) finds that it is more beneficial for both managers to receive the same signal μ if $\alpha > \beta$, i.e., if A and B are complements. If $\alpha < \beta$, i.e., if A and B are substitutes, it is more beneficial for both managers to receive a different signal. Thus, Crémer's result is very similar to the result by Milgrom and Roberts (1995).

As shown in the appendix, for uniformly or normally distributed misperceptions of the interaction effect the *reverse* result holds in our setup:

Proposition 9. *Given functional assumption* (1), *for complements, independent misperceptions that are distributed normally or uniformly, lead to a smaller performance decline than do perfectly correlated misperceptions.*

Only for very strong *substitutes* do independent misperceptions lead to larger performance declines than perfectly correlated misperceptions. This result thus offers a cautionary note. In modeling the effects of errors, the assumption of how errors affect choices is not innocuous. It can make a crucial difference whether actions are directly affected or whether it is the interaction between actions that is misperceived. If managers hold misperceptions with respect to interaction effects, the above result would indicate that if decisions are made on complementary activities, diversity of opinion is more beneficial than "groupthink"—it is preferable to have managers with varied misperceptions of interactions than managers who all share the same wrong belief (or to have centralized decision making by one mistaken manager).

One Manager with No Misperception. Last, we analyze the consequences of one manager (M1) having the correct belief about the interaction while the other manager (M2) still misperceives the interaction. The main question is whether in the presence of a decision maker who knows the true interaction effect and who, as a consequence, might be able to compensate for errors of the other decision maker, the results with respect to ignoring, over-, and underestimating interaction effects (Propositions 4–6) continue to hold. Proposition 10 establishes that this is indeed the case:

Proposition 10. *Given that M*1 *acts according to the true interaction, it is*:

(a) *more costly for M*2 *to ignore complements than substitutes,*

(b) *more costly to underestimate complements than substitutes, and*

(c) *more costly to overestimate complements than substitutes.*

The intuition behind this result is illuminating. For instance, if M2 ignores a substitute interaction and consequently overinvests, M2 decreases the marginal benefit for M1's investments. As a result, M1 will optimally underinvest and thereby partially compensate for M2's overinvestment. In contrast, if M2 ignores a complementary interaction and underinvests, M1's optimal response is also to underinvest, because M2's underinvestment has decreased the marginal benefit for M1. In this case, M1's ability to compensate for M2's mistake is much more restricted. These results are akin to Haltiwanger and Waldman's (1985) findings that agents with rational expectations can better compensate for behavior of agents with incorrect expectations if agents' actions cause congestion effects, i.e., interact as substitutes, than if agents' actions cause network effects, i.e., interact as complements.[9]

[9] It can also be shown that (a) given misperception δ_2, the optimal misperception of M1 is generally not $\delta_1 = 0$; and (b) informing one manager about the correct interaction strength while the other manager still has misperception δ can lead to a larger performance decline than having both managers with the same misperception δ.

5. Discussion and Conclusion

This paper set out to make a first attempt at formally studying the implications of misperceiving different types of interactions between activity choices. The overall flavor of the results is that misperceptions with respect to complements are more costly than misperceptions with respect to substitutes. Consequently, firms should be willing to invest more to reduce uncertainty about interactions between complementary activities than between substitute activities. While the specific results were derived using a particular functional form and thus await a more general analysis, the results show the importance of distinguishing between different types of interactions. Previous work frequently distinguished only between different degrees of interaction. As the results in this paper show, however, complementary interactions behave quite differently from substitute interactions. Thus, an explicit treatment of these two types of interactions can yield new insights. With the caveat in mind that the results concerning complementary and substitute interactions have only been shown in the context of a functional form that has well-behaved continuous second-order effects, we want to outline, nevertheless, a number of organizational implications of the central results. For purpose of illustration, we discuss the model's implications for division-based incentives and the allocation of tasks to different firms.

Division-Based Incentives. While division-based incentive systems ease decision making and allow firms to employ high-powered incentives to elicit effort, they may at the same time lead to the ignoring of division-spanning interaction effects. Under which conditions are these costs of employing division-based incentive systems likely to be large? To be concrete, consider two divisions within a firm that contemplate different investments such as an investment in capacity and an increase in the advertising budget, respectively. These two investments can interact in various ways: (1) They may be independent of each other. For instance, for DuPont an increase in its advertising budget for Lycra will have no impact on the marginal benefit of investing in more capacity in its titanium dioxide business; (2) The investments might be substitutes, in the sense of reducing the marginal benefit for each other. For instance, Procter and Gamble has various detergent brands (Cheer, Ivory Snow, Tide). Increasing the advertising for Tide, which would lead to larger sales of this product, is likely to reduce the marginal benefit of investing in a capacity expansion for a Cheer production line; (3) The investments might be complements if the products themselves are complements. For instance, if Nintendo increases its advertising for games, the marginal benefit of increasing production capacity for its game consoles is likely to increase.

Now let us consider the effects of different incentive systems or performance evaluation practices. In particular, how much weight should be put on division performance vs. firm performance for managers in each of the three cases above? The larger the emphasis on division performance is, the greater the degree to which the interaction between the investments is ignored or misperceived. Even though investment decisions interact in Cases 2 and 3 above, the model would suggest that Cases 2 and 3 should be treated differently. Because misperceptions with respect to substitutes tend to be less costly than with respect to complements, stronger division incentives can be employed in Case 2 than in Case 3. Casual observations about Procter and Gamble's decentralized brand manager structure and Nintendo's close coordination between software and hardware seem to bear out this result.

Task Allocation Across Firms. Related to the issue of intrafirm incentives is the question of allocation of tasks across firms. If interactions between activities are better understood if both activities are placed within the same firm than in different firms (Kogut and Zander 1992, Sridhar and Balachandran 1997), the model would suggest that the costs of placing complementary activities into different firms is larger than the cost of placing activities that interact as substitutes into different firms. For example, consider the question faced by a multiproduct firm of how to assign advertising campaigns to different agencies. On the one hand, there might be benefits to employing more than one advertising agency, such as greater variety of creativity or the ability to tap into the specialized expertise of different agencies. On the other hand, if the products are substitutes or complements for each other in the marketplace, the advertising investments will interact with each other (the marginal benefit to the firm as a whole of one campaign will be affected by the other campaign). The question arises—when are the costs of not (fully) taking these interactions into account high? That is, when are the costs of using different agencies high, and when are the costs of using different agencies low? The results of the model suggest that if the products are (partial) substitutes for each other, e.g., different breakfast products for Quaker Oats or different detergents offered by Procter and Gamble, the costs of using different agencies tend to be low. Conversely, if the two products are complements for each other, e.g., razors and shaving cream for Gillette, the complementary interdependence between the advertising campaigns is important, which might be more easily taken into account if the campaigns are organized by the same advertising agency. Quaker, Procter and Gamble, and Gillette have indeed split their advertising accordingly (*Standard Directory of Advertisers* 2001). At the same time, Gillette employs two different agencies for its razors and its electric shavers, presumably two substitute products.

Conclusion. While recent research has stressed the high interdependency among a firm's activities (e.g., Levinthal 1997, Milgrom and Roberts 1990, Porter 1996), the possibility of managers' misperceiving these interactions has not found much attention. A number of sources for such misperceptions exist, however, including the bounded rationality of decision makers in highly complex systems, outdated mental models that are only slow to change, and parochial incentive systems that lead managers to ignore externalities. This paper provided a first step in analyzing the consequences of such misperceptions. As the results showed, an important distinction needs to be made with respect to different types of interactions, since misperceptions of the interaction between complementary activities tend to be more detrimental than misperceptions of the interaction between substitute activities. While the existing literature has mainly focused on different degrees of interaction, e.g., loose vs. tight coupling, our analysis points to a further important distinction in the study of interaction effects. Possible future extensions of the analysis could include a more explicit model of how managers form their perceptions of interaction effects and how they update their beliefs as they receive feedback from the environment. Imposing more structure on the interaction effects in simulation models may provide another fruitful path to analyze the organizational design implications of misperceptions.

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Appendix: Proofs of Propositions
(More detailed proofs can be found in an electronic companion appendix on the *Management Science* website at ⟨mansci.pubs.informs.org⟩.) In the additive case (AC), a manager perceives the interaction to be $(\alpha+\delta)$ rather than α. In the multiplicative case (MC), the manager perceives $(1+\delta)\alpha$. For second-order conditions to be fulfilled, it is assumed that $|\alpha| < 2$, $|\alpha+\delta| < 2$ (for AC), and $|(1+\delta)\alpha| < 2$ (for MC). We also focus on relationship-conserving misperceptions; i.e., $\alpha+\delta > 0$ if $\alpha > 0$, and $\alpha+\delta < 0$ if $\alpha < 0$ (for AC) and $\delta \geq -1$ (for MC). For compactness, it is useful to compute the expressions for the performance declines for the general two-manager case and treat the one-manager case as a special case with $\delta = \delta_1 = \delta_2$.

For AC: $R(\alpha, \delta_1, \delta_2)$
$$= -\frac{(2+\alpha)\delta_2^2 + (2+\alpha)\delta_1\delta_2(\alpha+\delta_2) + \delta_1^2(2+\alpha+2\delta_2+\alpha\delta_2+\delta_2^2)}{(2-\alpha)(4-(\alpha+\delta_1)(\alpha+\delta_2))^2}. \quad \text{(A1)}$$

For MC: $R(\alpha, \delta_1, \delta_2)$
$$= -\frac{\alpha^2((2+\alpha)\delta_2^2 + \alpha(2+\alpha)\delta_1\delta_2(1+\delta_2) + \delta_1^2(2+\alpha(1+\delta_2(2+\alpha+\alpha\delta_2))))}{(2-\alpha)(4-\alpha^2(1+\delta_1)(1+\delta_2))^2}. \quad \text{(A2)}$$

Proof of Proposition 1a. *For any given misperception, it is less costly to misperceive substitutes than to misperceive (equally strong) complements*: $R(-\alpha, \delta) - R(\alpha, \delta) > 0$, *for all* $\alpha > 0$ *and all* δ.

AC: using (A1) with $\delta = \delta_1 = \delta_2$ yields:
$$\frac{\delta^2}{(2-\alpha)(2-\alpha-\delta)^2} - \frac{\delta^2}{(2+\alpha)(2+\alpha-\delta)^2} > 0. \quad \square$$

MC: using (A2) with $\delta = \delta_1 = \delta_2$ yields:
$$\frac{\alpha^2\delta^2}{(2-\alpha)(2-\alpha-\alpha\delta)^2} - \frac{\alpha^2\delta^2}{(2+\alpha)(2+\alpha+\alpha\delta)^2} > 0. \quad \square$$

In both cases, the denominator of the second term is larger than that of the first term.

Proof of Proposition 1b. *Claim* 1: *Reducing* $|\delta|$ *is always beneficial*: $\partial V^*/\partial\delta > 0$ *for* $\delta < 0$; $\partial V^*/\partial\delta < 0$ *for* $\delta > 0$. *Claim* 2: *Marginal changes of* δ *lead to larger performance changes for complements than for equally strong substitutes*: $|\partial V^*(\alpha,\delta)/\partial\delta| > |\partial V^*(-\alpha,\delta)/\partial\delta|$ *for* $\alpha > 0$, *where* $V^*(\alpha,\delta) = V(A^*(\alpha,\delta), B^*(\alpha,\delta), \alpha)$.

$$\text{AC:}\quad \frac{\partial V^*(\alpha,\delta)}{\partial\delta} = \frac{-2\delta}{(2-\alpha-\delta)^3}.$$

Claims 1 and 2 follow by inspection. □

$$\text{MC:}\quad \frac{\partial V^*(\alpha,\delta)}{\partial\delta} = \frac{-2\alpha^2\delta}{(2-\alpha-\alpha\delta)^3}.$$

Claim 1 follows by inspection. For Claim 2, recall that $\delta \geq -1$. Claim 2 holds with equality for $\delta = -1$ and strict inequality for $\delta > -1$. □

Proof of Proposition 2. *If misperceptions are distributed with probability density function* $h(\delta)$ *with mean zero, the marginal benefit of decreasing the variance of misperceptions is higher for complements than for equally strong substitutes.*

Assume $h(\delta)$ can be transformed into a different probability density function $g(\delta)$ that has a lower variance than $h(\delta)$ by moving probability mass from more extreme outcomes δ_2 to less extreme outcomes δ_1; i.e., $|\delta_1| < |\delta_2|$. For instance, h and g could be uniform distributions with the support of g being smaller than the support of h. Similarly, h and g could be normal distributions with the variance of g being smaller than the variance of h. If probability mass Δp is shifted from δ_2 to δ_1, the expected benefit increases by

$$\Delta p[V^*(\alpha,\delta_1) - V^*(\alpha,\delta_2)]. \tag{A3}$$

Proposition 2 claims that (A3) is larger for any level $|\alpha|$ if $\alpha > 0$ than if $\alpha < 0$:

$$\Delta p[V^*(\alpha,\delta_1) - V^*(\alpha,\delta_2)] > \Delta p[V^*(-\alpha,\delta_1) - V^*(-\alpha,\delta_2)] \quad \text{for all } \alpha > 0. \tag{A4}$$

We rewrite (A4) as:

$$[V^*(\alpha,\delta_1) - V^*(-\alpha,\delta_1)] > [V^*(\alpha,\delta_2) - V^*(-\alpha,\delta_2)]. \tag{A5}$$

Let $\Delta V(\delta) = V^*(\alpha,\delta) - V^*(-\alpha,\delta)$.
If $\delta_2 > \delta_1 > 0$, (A5) is true if $\partial\Delta V/\partial\delta < 0$. If $\delta_2 < \delta_1 < 0$, (A5) is true if $\partial\Delta V/\partial\delta > 0$.
Direct computation yields for AC: $\partial\Delta V/\partial\delta = (-4\alpha\delta(\alpha^2 + 3(2-\delta)^2))/((2+\alpha-\delta)^2(2-\alpha-\delta)^3)$ and for MC: $\partial\Delta V/\partial\delta = (-4\alpha^3\delta(1+\delta)(12+\alpha^2(1+\delta)))/((2-\alpha-\alpha\delta)^3(2+\alpha+\alpha\delta))$, both of which are negative for $\delta > 0$ and positive for $\delta < 0$ (recall $\alpha > 0$). □

Proof of Proposition 3a. *Stronger interactions do not always lead to higher performance declines.*

Substituting $\delta = \delta_1 = \delta_2$ into (A1) and differentiating with respect to α yields

$$\frac{\partial R(\alpha,\delta)}{\partial\alpha} = \frac{-\delta^2(6-3\alpha-\delta)}{(2-\alpha)^2(2-\alpha-\delta)^3} < 0 \quad \text{for all } \alpha \text{ and all } \delta. \tag{A6}$$

Thus, for the additive case, if $\alpha < 0$, the performance decline decreases as $|\alpha|$ increases. □

Proof of Proposition 3b. *For complements, stronger interactions lead to larger performance declines than for substitutes*:

$$\frac{\partial R(\alpha,\delta)}{\partial\alpha} + \frac{\partial R(-\alpha,\delta)}{\partial\alpha} < 0 \quad \text{for all } \alpha > 0. \tag{A7}$$

For AC, Proposition 3b follows directly from (A6).
For MC, the LHS of (A6) evaluates to:

$$\frac{8+2\alpha-\alpha^2(1+\delta)}{(2+\alpha)^2(2+\alpha+\alpha\delta)^3} - \frac{8-2\alpha-\alpha^2(1+\delta)}{(2-\alpha)^2(2-\alpha-\alpha\delta)^3}. \tag{A8}$$

(A8) is decreasing in δ and achieves its highest value in the admissible range of δ at $\delta = -1$. After substituting $\delta = -1$ into (A8), straightforward calculation shows that (A8) is negative for all $\alpha > 0$. □

Proof of Propositions 4–6. *Ignoring* (*under- and overestimating*) *substitutes is less costly than ignoring* (*under- and overestimating*) *equally strong complements.*

$$\text{For AC:}\quad R(-\alpha,\delta) - R(\alpha,-\delta) > 0 \quad \text{for } \alpha > 0. \tag{A9}$$

$$\text{For MC:}\quad R(-\alpha,\delta) - R(\alpha,\delta) > 0 \quad \text{for } \alpha > 0. \tag{A10}$$

Proposition 4 (*ignoring interactions*) *covers the case* $\delta = \alpha$ (*AC*) *or* $\delta = -1$ (*MC*).
Proposition 5 (*relationship-conserving underestimation*): $0 < \delta < \alpha$ (*AC*) *or* $-1 < \delta < 0$ (*MC*).
Proposition 6 (*overestimation*): $\delta < 0$ (*AC*) *or* $\delta > 0$ (*MC*).
Evaluating (A9) yields:

$$\frac{\delta^2}{(2-\alpha)(2-\alpha-\delta)^2} - \frac{\delta^2}{(2+\alpha)(2+\alpha-\delta)^2}. \tag{A11}$$

(A11) is decreasing in δ and achieves its lowest value in the admissible range of δ at $\delta = \alpha$. Straightforward calculation shows that (A11) is positive for all $\alpha > 0$ if $\delta = \alpha$. Hence, (A11) is positive for all $\delta \leq \alpha$, covering Propositions 4–6 for AC. □
Evaluating (A10) yields:

$$\frac{\alpha^2\delta^2}{(2-\alpha)(2-\alpha-\alpha\delta)^2} - \frac{\alpha^2\delta^2}{(2+\alpha)(2+\alpha+\alpha\delta)^2}. \tag{A12}$$

(A12) is increasing in δ and achieves its lowest value in the admissible range of δ at $\delta = -1$. Straightforward calculation shows that (A12) is positive for all $\alpha > 0$ if $\delta = -1$. Hence, (A12) is positive for all $\delta \geq -1$, covering Propositions 4–6 for MC. □

Proof of Proposition 7. *If the interaction parameter* α *is assumed to be randomly distributed, a firm will choose a lower variance of the signal* (*lower level of* d) *if* $0 \leq \alpha \leq 1$ *than if* $-1 \leq \alpha \leq 0$.

The manager receives signal $z = \alpha + \delta$, where $\delta \sim u[-d, d]$. We evaluate the gross benefit of choosing a value of d for the two cases of complements and substitutes.

The gross benefit of choosing d is given by:

$$E(V^*(d)) = \iint f(\boldsymbol{x}^*(z,d),\alpha)g(\alpha|z)h(z)\,d\alpha\,dz. \tag{A13}$$

The case of complements: $0 \le \alpha \le 1$.
(a) If $d \in [0, \frac{1}{2}]$:

$$E(V^*(d)) = \int_{-d}^{d}\int_{0}^{z+d} \frac{V_1}{2d}\,d\alpha\,dz + \int_{d}^{1-d}\int_{z-d}^{z+d}\frac{V_7}{2d}\,d\alpha\,dz + \int_{1-d}^{1+d}\int_{z-d}^{1}\frac{V_3}{2d}\,d\alpha\,dz.$$

(b) If $d \in [\frac{1}{2}, 1]$:

$$E(V^*(d)) = \int_{-d}^{1-d}\int_{0}^{z+d} \frac{V_1}{2d}\,d\alpha\,dz + \int_{1-d}^{d}\int_{0}^{1}\frac{V_2}{2d}\,d\alpha\,dz + \int_{d}^{1+d}\int_{z-d}^{1}\frac{V_3}{2d}\,d\alpha\,dz.$$

The case of substitutes: $-1 \le \alpha \le 0$.
(a) If $d \in [0, \frac{1}{2}]$:

$$E(V^*(d)) = \int_{-1-d}^{-1+d}\int_{-1}^{z+d} \frac{V_4}{2d}\,d\alpha\,dz + \int_{-1+d}^{d}\int_{z-d}^{z+d}\frac{V_7}{2d}\,d\alpha\,dz + \int_{-d}^{d}\int_{z-d}^{0}\frac{V_6}{2d}\,d\alpha\,dz,$$

(b) If $d \in [\frac{1}{2}, 1]$:

$$E(V^*(d)) = \int_{-1-d}^{-d}\int_{-1}^{z+d} \frac{V_4}{2d}\,d\alpha\,dz + \int_{-d}^{-1+d}\int_{-1}^{0}\frac{V_5}{2d}\,d\alpha\,dz + \int_{-1+d}^{d}\int_{z-d}^{0}\frac{V_6}{2d}\,d\alpha\,dz,$$

where

$$V_1 = \frac{4(2+\alpha-d-z)}{(4-d-z)^2},\; V_2 = \frac{4+4\alpha}{9},\; V_3 = \frac{4(1+\alpha+d-z)}{(3+d-z)^2},$$
$$V_4 = \frac{4(3+\alpha-d-z)}{(5-d-z)^2},\; V_5 = \frac{12+4\alpha}{25},\; V_5 = \frac{4(2+\alpha+d-z)}{(4+d-z)^2},\; V_7 = \frac{1}{2-z}.$$

The firm's optimal choice of d, d^*, is given by $\partial E(V^*(d^*))/\partial d = c'(d^*)$. It can be shown that the marginal benefit of decreasing d is always larger in the case of complements than in the case of substitutes. As a result, for any given convex cost function $c(d)$, the optimal level of imprecision concerning the interaction parameter is lower in the case of complements than in the case of substitutes. □

Proof of Proposition 8a. *With two managers who have randomly distributed misperceptions it is less costly to misperceive substitutes than to misperceive (equally) strong complements.*

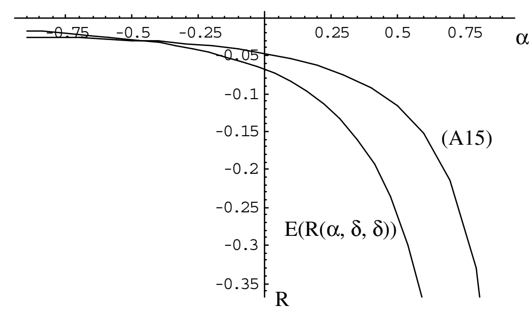
First, it can be shown (for both AC and MC), analogously to Proposition 1a, that

$$R(-\alpha, \delta_1, \delta_2) - R(\alpha, \delta_1, \delta_2) \ge 0 \quad \text{for all } \alpha \ge 0, \text{ and all } \delta_1, \delta_2. \quad \text{(A14)}$$

(To ensure that second-order conditions are met, we further restrict $0 \le \alpha \le 1$, $-1 < \delta_1 < 1$, $-1 < \delta_2 < 1$.)

(A14) holds because it can be shown that (A14) has a local minimum at $\delta_1 = \delta_2 = 0$ taking a value of 0. Since (A14) holds for any δ_1, δ_2, integrating (A14) over δ_1 and δ_2 given any probability density function of δ_1 and δ_2 (with appropriate support) will yield a positive number. □

Figure A-1



Proof of Proposition 8b. *Stronger interactions do not always lead to higher performance declines.*

An example will suffice to show that stronger interactions do not always lead to larger performance declines. Let δ_1, δ_2, be identically and independently distributed with $\delta_1 \sim u[-1, 1]$ and $\delta_2 \sim u[-1, 1]$. Then,

$$E(R(\alpha, \delta_1, \delta_2)) = \int_{-1}^{1}\int_{-1}^{1} R(\alpha, \delta_1, \delta_2)\frac{1}{2}\frac{1}{2}\,d\delta_1\,d\delta_2. \quad \text{(A15)}$$

In Figure A-1, (A15) is plotted as a function of α for AC. (To ensure that second-order conditions are fulfilled, α is confined to the interval $[-1, 1]$.) As Figure A-1 indicates, for substitutes an increase in the strength of interactions leads to a reduction in the performance decline. □

Proof of Proposition 9. *For uniformly or normally distributed misperceptions, independent misperceptions lead to a smaller performance decline than do perfectly correlated misperceptions in the case of complements.*

Figure A-1 includes a graph of $E(R(\alpha, \delta, \delta))$, i.e., the expected performance decline given perfectly correlated, uniformly distributed misperceptions and a graph of (A15), the expected performance decline given independently distributed misperceptions. As the Figure indicates, for $\alpha > 0$, independent misperceptions lead to a smaller performance decline, while for strong substitutes, perfectly correlated errors lead to a smaller performance decline. For MC, (A15) has a maximum at $\alpha = 0$ and crosses $E(R(\alpha, \delta, \delta))$ at $\alpha = 0$. Thus, independent misperceptions lead to a smaller performance decline than perfectly correlated misperceptions for $\alpha > 0$ and to a larger performance decline for $\alpha < 0$. If the misperceptions are assumed to follow a standard normal distribution truncated at -1 and 1, similar results are obtained. □

Proof of Proposition 10. *Propositions* 4–6 *hold with M*1 *having no misperception.*

A similar approach to that used in proving Propositions 4–6 is followed. Using (A1) and (A2), it is straightforward to show that:

$$\text{for AC:}\quad R(-\alpha, 0, \delta_2) - R(\alpha, 0, -\delta_2) > 0 \quad \text{for } \alpha > 0, \quad \text{(A16)}$$

$$\text{for MC:}\quad R(-\alpha, 0, \delta_2) - R(\alpha, 0, \delta_2) > 0 \quad \text{for } \alpha > 0. \;\square \quad \text{(A17)}$$

References

Athey, S. 2002. Monotone comparative statics under uncertainty. *Quart. J. Econom.* **117** 187–223.

——, J. Levin. 2000. The value of information in monotone decision problems. Working paper, MIT, Cambridge, MA.

Banker, R. D., A. A. Atkinson. 1996. *Management Accounting.* Prentice Hall, Englewood Cliffs, NJ.

Blackwell, D. 1951. Comparisons of experiments. *Proc. Second Berkeley Sympos. Math. Statist.* 93–102.

——. 1953. Equivalent comparisons of experiments. *Ann. Math. Statist.* **24** 265–272.

Bushman, R. M., R. J. Indjejikian, A. Smith. 1996. Aggregate performance measures in business unit manager compensation: The role of intrafirm interdependencies. *J. Accounting Res.* **33**(Supplement) 101–128.

Crémer, J. 1990. Common knowledge and the co-ordination of economic activities. M. Aoki, B. Gustafsson, O. Williamson, eds. *The Firm as a Nexus of Treaties.* Sage, London, U.K.

——. 1993. Corporate culture and shared knowledge. *Indust. Corporate Change* **2** 351–386.

Dearden, J. 1987. Measuring profit center managers. *Harvard Bus. Rev.* **65**(September–October) 84–88.

Firestone, W. A. 1985. The study of loose coupling: Problems, progress, and prospects. *Res. Sociology Ed. Socialization* **5** 3–30.

Galbraith, J. R. 1977. *Organization Design.* Addison-Wesley, Reading, MA.

Geanakoplos, J., P. R. Milgrom. 1991. A theory of hierarchies based on limited managerial attention. *J. Japanese Internat. Econom.* **5** 205–225.

Glassman, R. B. 1973. Persistence and loose coupling in living systems. *Behavioral Sci.* **18** 83–98.

Groves, T., R. Radner. 1972. Allocation of resources in a team. *J. Econom. Theory* **4** 415–441.

Haltiwanger, J., M. Waldman. 1985. Rational expectations and the limits of rationality: An analysis of heterogeneity. *Amer. Econom. Rev.* **75** 326–340.

Hambrick, D. C., P. A. Mason. 1984. Upper echelons: The organization as a reflection of its top managers. *Acad. Management Rev.* **9** 193–206.

Hammond, J. H. 1993. Quick response in retail/manufacturing channels. J. Hausman, R. Nolan, eds. *Globalization, Technology, and Competition.* Harvard Business School Press, Boston, MA.

Hayes, R. H., R. Jaikumar. 1988. Manufacturing's crisis: New technologies, obsolete organizations. *Harvard Bus. Rev.* **66**(September–October) 77–85.

Henderson, R. M. 1993. Underinvestment and incompetence as responses to radical innovation: Evidence from the photolithographic alignment equipment industry. *RAND J. Econom.* **24** 248–270.

——, K. B. Clark. 1990. Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Admin. Sci. Quart.* **35** 9–30.

Hustad, T. P. 1996. Reviewing current practices in innovation management and a summary of selected best-practices. M. C. Rosenau, A. Griffin, N. Anschuetz, G. Castelion, eds. *The PDMA Handbook on New Product Development.* John Wiley, New York.

Jaikumar, R. 1986. Postindustrial manufacturing. *Harvard Bus. Rev.* **64**(6) 69–76.

Jewitt, I. 1989. Choosing between risky prospects: The characterization of comparative statics results, and location independent risk. *Management Sci.* **35** 60–70.

Keating, A. S. 1997. Determinants of divisional performance evaluation practices. *J. Accounting Econom.* **24** 243–273.

Khandwalla, P. N. 1973. Viable and effective organizational designs of firms. *Acad. Management J.* **16** 481–495.

Kiesler, S. B., L. Sproull. 1982. Managerial response to changing environments: Perspectives on problem sensing from social cognition. *Admin. Sci. Quart.* **27** 548–570.

Kogut, B., U. Zander. 1992. Knowledge of the firm, combinative capabilities, and the replication of technology. *Organ. Sci.* **3** 383–397.

Kremer, M. 1993. The O-ring theory of economic development. *Quart. J. Econom.* **108** 551–575.

——, E. Maskin. 1996. Wage inequality and segregation by skill. Working paper No. 5718, National Bureau of Economic Research, Cambridge, MA.

Lehman, E. L. 1988. Comparing location experiments. *Ann. Statist.* **16** 521–533.

Levinthal, D. A. 1997. Adaptation on rugged landscapes. *Management Sci.* **43** 934–950.

March, J. G., H. A. Simon. 1958. *Organizations.* John Wiley & Sons, New York.

Marschak, J., R. Radner. 1972. *Economic Theory of Teams.* Yale University Press, New Haven, CT.

Milgrom, P. R., J. Roberts. 1990. The economics of modern manufacturing: Technology, strategy, and organization. *Amer. Econom. Rev.* **80** 511–528.

——, ——. 1992. *Economics, Organization, and Management.* Prentice Hall, Englewood Cliffs, NJ.

——, ——. 1995. Complementarities and fit: Strategy, structure, and organizational change in manufacturing. *J. Accounting Econom.* **19** 179–208.

——, C. Shannon. 1994. Monotone comparative statics. *Econometrica* **62** 157–180.

Miller, D., P. H. Friesen. 1984. *Organizations: A Quantum View.* Prentice Hall, Englewood Cliffs, NJ.

Murmann, J. P., M. L. Tushman. 1997. Organizational responsiveness to environmental shock as an indicator of organizational foresight and oversight: The role of executive team characteristics and organizational context. R. Garud, P. R. Nayyar, Z. B. Shapira, eds. *Technological Innovation.* Cambridge University Press, New York.

Nelson, R. R., S. G. Winter, Jr. 1982. *An Evolutionary Theory of Economic Change.* Harvard University Press, Cambridge, MA.

Orton, J. D., K. E. Weick. 1990. Loosely coupled systems: A reconceptualization. *Acad. Management Rev.* **15** 203–223.

Persico, N. 2000. Information acquisition in auctions. *Econometrica* **68** 135–148.

Porter, M. E. 1996. What is strategy? *Harvard Bus. Rev.* **74**(6) 61–78.

Radner, R. 1972. Teams. C. B. McGuire, R. Radner, eds. *Decision and Organization.* North-Holland, Amsterdam, The Netherlands.

Reece, J. S., W. R. Cool. 1978. Measuring investment center performance. *Harvard Bus. Rev.* **56**(May–June) 1–11.

Rivkin, J. W. 2000. Imitation of complex strategies. *Management Sci.* **46** 824–844.

Ruekert, R. W., O. C. Walker, Jr. 1987. Interactions between marketing and R&D departments in implementing different strategies. *Strategic Management J.* **8** 233–248.

Schaefer, S. 1999. Product design partitions with complementary components. *J. Econom. Behavior Organ.* **38** 311–330.

Shannon, C. 1995. Weak and strong monotone comparative statics. *Econom. Theory* **5** 209–227.

Siggelkow, N. 2001. Change in the presence of fit: The rise, the fall, and the renaissance of Liz Claiborne. *Acad. Management J.* **44** 838–857.

——. Evolution toward fit 2002. *Admin. Sci. Quart.* **47** 125–159.

Simon, H. A. 1957. *Models of Man: Social and Rational; Mathematical Essays on Rational Human Behavior in a Social Setting.* John Wiley, New York.

Sridhar, S. S., B. V. Balachandran. 1997. Incomplete information, task assignment, and managerial control systems. *Management Sci.* **43** 764–778.

Standard Directory of Advertisers. 2001. National Register Publishing Co., Skokie, IL.

Thompson, J. D. 1967. *Organizations in Action.* McGraw-Hill, New York.

Topkis, D. M. 1978. Minimizing a submodular function on a lattice. *Oper. Res.* **26** 305–321.

Weick, K. E. 1976. Educational organizations as loosely coupled systems. *Admin. Sci. Quart.* **21** 1–19.

——. 1982. Management of organizational change among loosely coupled elements. P. S. Goodman, ed. *Change in Organizations.* Jossey-Bass, San Francisco, CA.

Wilson, B. L., H. D. Corbett. 1983. Organization and change: The effects of school linkages on the quantity of implementation. *Educational Admin. Quart.* **19** 85–104.

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