**Real Real Options: A Behavioral Theory of Investment Under Uncertainty**

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## Abstract

Strategic investment decisions often involve substantial uncertainty, e.g., developing a new technology or expanding into a new line of business. Contemporary theory, based on a real options approach, suggests a decision logic that accounts not only for the potential future returns from an investment, but also the additional returns from management's ability to respond flexibly to new information. This approach, rooted in the theory of financial options, has been criticized because it makes assumptions regarding the decision-making environment that are unlikely to hold for real-world investments. Our key contribution is the development of theory that describes how economic and informational properties of the environment, as well as behavioral properties of decision-makers, influence strategic investment decisions. We develop a model that accounts for these informational and behavioral realities by recognizing that a real options model of decision making and a bandit model of experiential learning are fundamentally interrelated models of sequential decision-making under uncertainty. Our model nests both the Black-Scholes model and the learning model, providing testable predictions about how managerial decisions will vary across contexts that differ in uncertainty. These predictions, which contrast with those of standard real options theory, appear to be broadly consistent with anecdotal evidence that managers tend to forgo the potential value of flexibility when uncertainty is high.

## 1. Introduction

A central and ubiquitous activity of the firm is making investment decisions when there is substantial uncertainty about future returns — e.g., building a new production facility, developing a new technology, entering a new country, acquiring a rival, forming a joint venture, or expanding into a new business. These decisions are important because they relate to fundamental questions in the field of strategic management regarding why firms differ in their activities, capabilities, and performance (e.g., Rumelt, Schendel, and Teece, 1991, 1994). In managerial practice, the dominant approach to the evaluation of investment opportunities is discounted cash flow (DCF). The research literature in management (dating to Bowman and Hurry 1993, Kester 1984, Kogut 1991), building on work in finance (Myers 1977), has emphasized the additional insight into the value of flexibility provided by a real options approach. These approaches allow a manager to assess the merits of an investment while accounting for uncertainty associated with future outcomes.

The extant literature points to reasonably clear conditions under which a real options approach, which values flexibility, is likely to substantively influence managerial decisions about strategic investments. A central shortcoming of DCF is that it employs limiting assumptions about the reversibility and timing of investment that ignores additional returns from management's ability to respond flexibly to new information. The real options approach provides a means to estimate the value of flexibility associated with making a limited initial investment today that provides a preferential claim on the opportunity to make additional investments in the future. As a consequence, when uncertainty is low, DCF is sufficient because the value of flexibility is small. At higher levels of uncertainty, the potentially more substantial value associated with flexibility suggests that real options is the dominant approach. Yet the use of real options, even when it is clearly appropriate, seems limited. Indeed, while the popular managerial press ~~continually~~ extols the benefits of valuing flexibility via a real options approach (e.g., Courtney, Kirkland, and Viguerie, 1997; Coy, 1999; Luehrman, 1998), diffusion into practice has been limited. One question that has often been asked in the business press is: "Will real options take root?" (Teach 2003).

So why is the formal mathematical logic of real options less used in practice than theory would suggest? One answer is that intuition on the value of flexibility is inherently flawed. Yet, good managers intuitively understand the value of flexibility — they are "naive option-takers" — even in the absence of a deep understanding of the mathematics of Black-Scholes' (1973) Nobel prize winning theory. An alternative answer, to which we subscribe, is that the conventional theory of real options predicts a value of flexibility far in excess of that which can be effectively realized by firms. Managerial decisions made in accordance with the strict mathematics of conventional real options theory leads to decision errors with substantial downside risk that is, understandably, avoided by practicing managers.

Real options, like DCF, has limiting assumptions. In particular, it assumes that managers have precise information regarding the relevant project parameters and are able to act in accordance with that information to determine whether to exercise or terminate a project. Yet a large literature points to informational properties of the environment (Arrow 1974, Lippman and Rumelt 1982, Levinthal 1997) and behavioral properties of firms (Simon 1955, Bower 1970, Kahneman and Tversky 1979) that are at odds with the assumptions in the real options approach to project valuation. These informational and behavioral realities suggest that practical implementation of these standard tools oblige managers to make inappropriate simplifying assumptions, and may account for the observation that real options is less used in practice than would otherwise be expected. This is consistent with van Putten and MacMillan's (2004) observation that managers, applying the real options approach, "overestimate the value of uncertain projects, encouraging companies to overinvest in them".

We develop a model of sequential decision making under uncertainty that takes seriously the informational and behavioral realities of strategically important firm investment decisions such as acquisitions and R&D. This model nests discounted cash flow and real options within a behavioral theory of investment. Building on the substantial debate regarding the relative role of economic and behavioral approaches (e.g., Adner and Levinthal, 2004a, 2004b; McGrath, Ferrier, and Mendelow, 2004; Kogut and Kulatilaka, 2004), we link the economic logic of discounted cash flow and real options with a formal theory of learning under uncertainty (e.g., March 1996, Posen and Levinthal 2012) that accounts for common realities of decision-making by firms. Our key theoretical insight is that a real option model of decision making under uncertainty and a bandit model of learning under uncertainty are fundamentally interrelated models of sequential decision-making. In the resulting computational model, real options and learning approaches to sequential decision-making are corner solutions in a more general framework that accommodates a wide variety of behavioral and informational assumptions. The resulting findings suggest how deviations from rational assumptions limit both the effectiveness of real options as a tool of decision making and the ability of firms to leverage the value of flexibility inherent in strategic investment decisions.

## 2. Theoretical Logic of Real Options

In this section and the next, we seek to outline the basic theoretical foundations of a behaviorally realistic theory of real options. We are concerned with investment decisions where there is uncertainty about future outcomes from a particular investment (e.g., building a new production facility or developing a new technology). We construct our theoretical apparatus by examining the existing approaches to evaluating investment opportunities. It is generally recognized that project evaluation should be based on the contribution to future profitability. This idea has long been institutionalized using the terminology of net present value (NPV), a metric that provides a guide for a firm's decisions. We proceed by reviewing the discounted cash flow (DCF) approach as a precursor to real option analysis. We then review the theoretical logic of real options, highlighting the additional insight (above DCF) this approach provides to estimating a project's value. We conclude this section by discussing the limitations to the real options approach.

Our discussion in this section lays the foundation for the development of a behavioral theory of real options in Section 3. This extension of traditional real options theory, which accounts for both the informational realities and the behavioral deviations from rationality inherent in a real (rather than financial) world, builds on formal theory of learning from experience (e.g., Bush and Mosteller 1955, Newell and Simon 1972, Lave and March 1975, Levinthal and March 1981).

*Discounted Cash Flow*

The common and traditional approach to calculating the NPV of an investment opportunity involves the calculation of discounted cash flow (e.g., Fisher 1930, Brealey, Myers, and Allen 2010). While the strategy literature has historically paid less attention to the analytical tools used by managers in the resource allocation process, the language and intuition of DCF is common (e.g., Ghemawat 1991). DCF requires the development of a cash flow "model" that depicts expected costs and revenues over time. These cash flows are then discounted back to a single point in time using an appropriate discount rate. This process results in the value of a project being summarized by a single parameter, NPV (or analogously, internal rate of return or payback period).

To consider DCF more formally, suppose we have only two time periods, $t = 0$ and $t = 1$, where the former reflects the initial decision time. We write the current value, $N_0$, of an investment opportunity as the cash flows at these two times:

$$N_0 = I_0 + \frac{F_1}{(1+r_{dcf})} \quad (1)$$

where $I_0$ is the initial investment and $F_t$ is the cash flow at time $t$. The discount rate, $r_{dcf}$, is a function of a firm's cost of capital, as well as an adjustment for uncertainty in a given project's cash flows. In Equation 1, a firm commits an investment $I_0$ at $t$=0, with the expectation of a resulting future cash flow, $F_1$, at $t$=1. While there are many practical issues in estimating the expected cash flows and appropriate discount rate, the basic principle is fairly simple—calculate the NPV of an investment project using DCF, and invest if it is positive (e.g., Dixit & Pindyck, 1994).

Despite its widespread use, fundamental assumptions underlying the DCF model lead to a number of well-known theoretical limitations (Dixit and Pindyck 1994). DCF assumes that investments are irreversible in the sense that the project cannot be terminated, and prior investments are sunk. A manager makes a project decision at $t$=0 that fixes her expectations of cash flows $F_t$ for all $t$, irrespective of what occurs between time 0 and time $t$. Additionally, investment opportunities in DCF approach are 'now or never' propositions—it is typically assumed that a similar opportunity will not exist in the future. While decision-makers may attempt to capture the discretionary nature of subsequent investments through the use of terminal values, these values are notoriously imprecise and almost always represent a large proportion of the total project value (Kester, 1984).

In sum, the utilization of DCF presumes that management is passive, fully committed to a particular strategic investment approach at the start of the project (e.g., Luehrman, 1998). It precludes managerial discretion to act flexibly on new information and a changing world, and is at odds with economic and management theory which argues that decision-makers should pursue firm- and industry-specific resources to generate competitive advantage over time (e.g., Lippman and Rumelt, 1982). As such, it has been noted that "DCF does not reflect the value of management" (Brealey, Myers, and Allen 2010 p.554).

*Real Options*

Real options logic, at least in principle, provides a useful framework for addressing some of the limitations in the DCF approach to evaluating investment projects. In contrast to traditional discounted cash flow techniques, the real option approach recognizes that investments are at least partially reversible, managers are capable of reacting flexibly to changing market conditions, and that risk may vary over different investment stages (e.g., Amram and Kulatilaka, 1999; Copeland and Antikarov, 2001; Dixit, 1989). Moreover, real options logic provides a method for evaluating the benefit associated with the ability to react flexibly. In so doing, the real options approach provides a means to account for the benefits of deferral and/or sequential decision-making in response to the arrival of new information that resolves uncertainty about the project's future prospects. Numerous types of real options have been identified in the literature, including the option to defer, the option to stage investment, the option to alter operating scale, the option to abandon operations, the option to switch inputs or outputs, and the option to grow (Trigeorgis, 1996).

A real option is analogous to a financial option (Black and Scholes, 1973), which gives an investor the right, but not the obligation, to purchase or sell a valuable asset (such as a share of stock) at a future (expiration) date at a certain (exercise) price. In a real option, the asset is not a financial stock, but rather a real asset, for example, a new production facility, or a new technology.

At the core of the real options approach to valuing a project is the observation that uncertainty about the value of the project may be resolved over time, and as such, the value of flexibility is that associated with delaying full investment until project uncertainty is resolved. The payoff diagram depicting this "option" feature leads to an asymmetry in the distribution of returns—by purchasing an option, the owner gains access to greater upside potential than downside exposure. Empirical findings in the management literature are consistent with this approach. Studies have provided evidence conforming with the base logic of deferral options (e.g., Folta and O'Brien, 2004; Miller and Reuer, 1998), growth options (e.g., McGrath and Nerkar, 2004; Miller and Folta, 2002), pursuit of option claims in collaborations (e.g., Chi, 2000; Chi and McGuire, 1996; Folta, 1998); and the performance consequences of an option approach in multinational settings (e.g., Reuer and Leiblein, 2000).

<< Insert Figure 1 about here >>

There are three main elements of the option process. For simplicity of exposition, we focus on a "call" option — the option to buy (rather than a "put" option). First, the firm expends a small price, C, for a preferential claim to (exercise the option and) fully invest at a future time. Second, information arrives regarding, for example, demand, technology, or regulations, that resolves project uncertainty regarding the state of future cash flows. Third, the firm determines whether or not to proceed with the follow-on investment. If uncertainty is resolved favorably because the asset value, $S_1$, is greater than the exercise price, K, option logic presumes that the decision-maker will respond by exercising the option and investing more fully. In doing so, the firm captures the value provided by the preferential claim associated with the initial option investment. In the event that uncertainty is resolved unfavorably, option logic assumes the firm will terminate the project, incurring a relatively small loss associated with the initial investment, C. The value of the option increases with the value of the underlying asset, $S_0$, the extent of project uncertainty, and the length of the option. Here, the underlying asset corresponds to some feature of the project (e.g., an R&D lab) that embodies uncertainty and hence option value.

It is worth noting the contrast to the DCF approach discussed earlier. In Equation 1, at t=0, an up front investment, $I_0$ , commits the firm to undertaking the project and receiving a net cash flow, $f_1$, discounted by $r_{dcf}$. In making this commitment, the DCF approach requires an estimate of the cash flow at t=1, even though there may be substantial uncertainty surrounding this estimate. Yet in practice, there appear to be many contexts in which a firm need not fully commit to a project at t=0. Instead, the firm can make a smaller initial investment, $C$, that secures the right, but not the obligation, to make a follow-on investment $K$ at t=1, contingent on the realized cash flow at t=1 being sufficiently high.

For instance, a firm contemplating a national roll-out of a new product may invest in a real option by first introducing the product to a test market. The test market will enable the firm to form a better estimate of demand for the product, without fully committing to a national campaign. The cost of the test market is C, and the cost to engage in a full roll-out after the test is K. After conducting the test, the firm has reduced the uncertainty in the value of future cash flows because of the new information about demand, and estimates $S_1$. If $S_1$ is greater than the strike price K, the firm exercises the option by rolling out the product nationally.

To formally capture this logic, we begin by writing an expression that reflects the upside returns of taking a call option. The value of the option, e.g., the value of flexibility, Z, associated with the option:

$$Z = max\,[\,S_1 - K, 0]/(1 + r_{rf}) \qquad (2)$$

where K is the price paid to exercise the option, commonly called the strike price, $S_1$ is the price of the underlying asset after uncertainty is resolved at t=1, and $r_{rf}$ is the risk-free rate of return. As discussed in footnote 2, the ability to construct a risk neutral hedge "squeezes" risk out of the valuation problem and suggests that the risk free rate is the appropriate discount rate (e.g,. Trigeorgis, 1996: 75). The uncertain future price of the asset at t=1, $S_1$, is assumed to be a random variable because it is the outcome of a stochastic process that depends on the initial price of the underlying asset $S_0$, and the extent of project uncertainty σ, such that:

$$S_1 = f(S_0,\ \sigma)\ . \quad (3)$$

In the Black-Scholes formulation (see Steele 2001 for a detailed discussion of the derivation), the function represented in Equation 3 takes the specific form of a random walk defined by geometric Brownian motion, such that:[2]

$$S_1 = S_0 exp(r_{rf} - \sigma^2/2 + \sigma v)\ , \quad (4a)$$

which, expressed in log form (indicated by lower case *s* rather than upper case *S*), is:

$$s_1 = s_0 + r_{rf} - \sigma^2/2 + \sigma v\ , \quad (4b)$$

where $v$ is the standard unit normal distribution, σ represents project uncertainty, and $r_{rf}$ is the risk-free rate of return.[3] In the Black-Scholes formulation of geometric Brownian motion, $v$ has a unit normal distribution. Note that project uncertainty is assumed to be exogenous and to reflect the degree of unpredictability about how factors external to the firm will affect the future value of the project, e.g., currency exchange rates (e.g., Campa, 1994).[4] The distribution of $S_1$ is an increasing function of project uncertainty σ. Defined this way, value of flexibility, $Z$ in Equation 2, has the same distribution as the underlying asset in a financial option, so the expected payoff can be solved using the Black-Scholes option pricing equation.

The *project value*, P, which is equivalent to an NPV but calculated via a real options approach, includes two components (Trigeorgis 1996): the passive project value that ignore flexibility, $S_0$, obtained from the DCF analysis, and the value of flexibility, Z, obtained from the real options analysis, less the cost of taking the option, C, such that:

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[2] In the finance literature, there are known deviations from the Black-Scholes predictions. To address these deviations, research examines alternative functional forms of Equation 4 that do not rely on geometric Brownian motion. For instance, Christoffersen, Heston, and Jacobs (2009) show how a two-factor stochastic volatility model can explain fluctuations in the level and slope of discrepancies between observed option value and Black-Scholes benchmarks (e.g., so called volatility "smirks" or "smiles").

[3] Standard financial option models assume that the risk characteristics of the underlying asset do not change over the life of the option, usually expressed via a constant volatility assumption. Hence a standard, risk free rate may be applied as the discount rate at each decision point, allowing for risk neutral valuation. Under real options valuation, however, managements' actions may change the risk characteristics of the project in question, and the required rate of return could differ depending on realized state. As such, a premium over risk free may be required, invalidating the risk neutrality assumption. Since our focus here is on bridging valuation logics and not on technical issues regarding discount rates, we follow the financial options literature in using the risk-free rate.

[4] The management literature on real options highlights not only exogenous project uncertainty, but also endogenous project uncertainty. As Cuypers and Martin (2010: 50-51) note, "endogenous uncertainty is resolved is the share of total value uncertainty that the firm resolves by taking action to influence outcomes (Chi and Seth, 2001; Roberts & Weitzman, 1981). In this paper, we abstract from endogenous uncertainty in value.

$$P = N_0 + Z - C\,. \tag{5}$$

The Black-Scholes solution defines an indifference point — the option price at which a firm would be indifferent between holding and not-holding the option, which we label C*. Thus, it is the maximum a firm should pay for the option, for a given strike price, K. In particular, the Black-Scholes option value is given by:

$$C^* = S_0 N(d_1) - Ke^{-r_f} N(d_2) \tag{6}$$

$$with: \quad d_1 = \frac{ln(S_0/K)+(r_{rf}+\sigma^2)}{\sigma} \;;\; \text{and} \quad d_2 = d_1 - \sigma\,,$$

where the parameters $S_0$ , $K$ , and $r_{rf}$ are discussed above, and N is the CDF of the standard normal distribution.

In addition to providing a descriptive way to characterize the investment profile of real assets, option theory provides a means to guide decision-making by estimating the value of flexibility. The firm's decision calculus appears to be simple. Assume that the discount rate in Equation 1, $r_{dcf}$, includes the hurdle rate of return necessary for investment. A firm would calculate the project value, P, and proceed with the project if $P > 0$. As such, if $S_0 > 0$, the firm would invest in the project, and indeed, if $S_0 > Z\text{-}C$ the firm may forgo the option and simply invest. If $S_0 < 0$, then the firm would not invest in the project.

However, the equations above also point to the conditions under which the firm would invest in a negative DCF project. It extends the choice set to invest fully today, invest flexibly today, or do not invest. If $S_0 < 0$ but $Z\text{-}C > S_0$, then the firm would invest in the option even though the DCF is negative, because the net payoff to the option is sufficiently offsetting. At $t = 1$, after project uncertainty is resolved, the firm would then make the decision to exercise the option if $S_1 > K$, or terminate otherwise.

The real options approach to valuing investments under uncertainty takes the active role of the manager seriously. DCF envisions a passive management, fully committed to a particular strategic investment approach at the start of the project (e.g., Luehrman, 1998), precluding managerial discretion to act flexibly on new information and a changing world. Real options logic suggests that a firm may invest in a negative DCF project if the option value is sufficiently large. While this is a central implication of using real options analysis, the validity of the claim rests on the firms' ability to effectively make the decision to exercise or terminate the option, which has been the subject of substantial debate in the management literature (e.g., Adner and Levinthal, 2004a, 2004b; McGrath, Ferrier, and Mendelow, 2004; Kogut and Kulatilaka, 2004).

By recognizing that managers can flexibly respond to changes in the state of the world (resolution of project uncertainty), the real option literature encourages managers to engage in behaviors that seek upside opportunities and reduce risk. While option logic does not provide a theory of competitive advantage, it describes how exploratory investments may confer claims on potentially lucrative opportunities. Firms generate competitive advantage by developing and taking advantage of preferential claims on the right to act flexibly. In other words, managers generate advantage by leveraging insight regarding changes in factors such as market power, the demand for scarce resources, barriers to imitation, or the ability to spread the advantage to new uses with the option valuation approach. As noted by Kogut (1991), real options logic encourages firms to confront fundamental sources of uncertainty proactively, rather than merely attempting to buffer against or avoid uncertainty.

Yet real options theory is, in its strict form, predicated on a particular set of assumptions that derive from its roots in financial theory. Employed in the real context, rather than a financial context, the options approach solves the problems that “DCF does not reflect the value of management” (Brealey, Myers, and Allen 2010 p.554). The real option approach puts managers in a central role of making and revising investment decisions sequentially. However, it does so by making an alternative assumption — not about the relevance of managers, but rather, about the informational environment in which managers act, and the efficacy of their decision making.

Real options assumes that managers have accurate and timely information on all of the central parameters of the model including the: cost of their initial investment (*C*), strike price at which they can exercise the option (*K*), project uncertainty (σ), value of the project if fully invested today ($S_0$), and value of the project at exercise time ($S_1$). In the context of financial options, this data is gathered in part by means of a “replicating portfolio” to assess uncertainty, and other data, such as the price at $t$=0 that is easily observable from real-time market data (e.g., on a Reuters or Bloomberg terminal). Of course, for real options, these informational assumptions are highly problematic (Borison 2005) — managers cannot generally construct a replicating portfolio, and they certainly don’t have a Reuters terminal to provide perfect information on the value of a project at a given point in time. Additionally, real options assumes that managers behave optimally — they act effectively on the information, exercising the option when it is in the money and declining to do so otherwise. While this decision task is relatively simple if a manager has perfect information, it is cognitively challenging in the real (non-financial) world.

## 3. Toward a Behavioral Theory of Real Options

Our central theoretical insight is that the informational and behavioral assumptions of real options can be relaxed — and formally modeled — if we recognize that there is not one, but two parallel streams of research on sequential decision-making under uncertainty: real options and learning. Like real options theory, experiential learning theory focuses on a firm's potential to act flexibly when new information arises. In our discussion below, we derive a behavioral theory of real options that nests, at one corner of parameter space, the Black-Scholes model of real options investment under uncertainty (Black and Scholes 1973), and at the other corner of parameter space, a Bandit model of learning under uncertainty (Gittins 1979, Denrell and March 2001, Posen and Levinthal 2012).

The claim that firms learn from their own experience in a sequential manner is uncontroversial. It is a central theoretical concept in the management literature, building on the Carnegie School tradition (March and Simon 1958, Cyert and March 1963). As Arrow (1962: 155) notes, "one empirical generalization is so clear that all schools of thought must accept it …[L]earning is the product of experience. Learning can only take place through the attempt to solve a problem". The basic premise is that feedback from experience is used to enhance the efficacy of subsequent decisions (Herriott et al. 1985, March and Olsen 1975). Indeed, the theory of experiential learning is so broadly employed in the management literature, it is beyond the scope of this paper to review. To provide just a few relevant examples, experiential learning theory is central to foundational ideas in management including: organizational learning curves (e.g., Argote 1999, Lieberman 1984), exploration and exploitation (March 1991), resource based view (e.g., Dierickx and Cool 1989; Ethiraj, Kale, Krishnan, and Singh 2005; Leiblein, 2011), and adaptation to change (Davis, Eisenhardt, and Bingham 2009, Teece 2007, Posen and Levinthal 2012).

A central concept underlying theories of learning in the management literature is bounded rationality (Simon 1955). Because of bounded rationality, sequential decision-making is viewed as a search process in which a firm must learn about the merits of alternative actions. Bounded rationality is not necessarily an impediment to decision-making. If the decision problem is sufficiently simple, bounded rationality may not bind. For example, if a firm that manufactures heavy machinery is deciding whether to invest in a fleet of semi-trailers or sub-compact cars to build a nationwide delivery fleet, then bounded rationality is unlikely to be an issue. The problem is simple — a sub-compact car is not suitable. A more challenging problem would be that of whether to buy a fleet of semi-trailers or outsource outbound logistics. For this problem, bounded rationality certainly binds (Williamson 1979).

Likewise, for financial options, bounded rationality does not substantially bind. As we noted above, a decision-maker can typically construct a replicating portfolio to assess uncertainty, and has perfect information about asset prices (e.g., by looking at a Reuters terminal). As such, the firm is unlikely to make any informational or behavioral errors — it exercises an option only when it is profitable to do so, and chooses not to exercise only when it is unprofitable to exercise[5].

In contrast, for real options, the limitations imposed by bounded rationality certainly bind on the firm. Indeed, management literature points to two distinct, but integrally related issues: informational and behavioral. Adner and Levinthal (2004a, 2004b) highlight the informational challenges of real options. Firms do not have Reuters' terminals. Instead, they have noisy signals about the key decision inputs. McGrath, Ferrier, and Mendelow (2004) and Kogut and Kulatilaka (2004) highlight the behavioral challenges of real options. Firms must appropriately decide to execute or terminate an option. Indeed, the behavioral challenge is exacerbated if informational conditions are less than perfect.

*Key Conceptual Elements of a Learning Model*

Two dimensions of an experiential learning model are core to our theory: decision-making based on beliefs, and belief-updating based on new information. We discuss each in turn below, drawing on the formal Bandit model (Denrell and March 2001, March 2010, Posen and Levinthal 2012), which has been called the canonical model of learning under uncertainty (Holland 1975).

First, in a learning model, decision-making is based on beliefs about the merits of the choice alternative. That is, while there is some latent true value, a firm cannot "know" this value in the fully rational sense. Instead, there are beliefs about the latent values — these beliefs are estimates of the true value. These beliefs may be informative, relatively highly correlated with the true but unobserved value, or they may be uninformative, only loosely correlated with the true value. For instance, a manager may hold beliefs about the value and uncertainty underlying a given investment due to familiarity with "this sort of project" (e.g., they favor the use of consumer insight modeling to estimate the value of a project).

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[5] Research in the finance literature has examined implications of incomplete imperfect information and information asymmetry on valuation models. For instance, Duffie and Lando (1999) demonstrate how incomplete information affects the valuation of risky debt. Back (1993) shows how asymmetric information affects one's ability to construct a replicating portfolio and price options. Grenadier (1999) describes how asymmetric information between rivals can lead to information cascades that affect realized option prices. Grenadier and Wang (2005) show how asymmetric information between principal and agent can decrease a manager's willingness to wait. While finance research acknowledges information issues, our information problem is even more basic-- can a decision-maker identify the true asset price and make an appropriate decision at the time of exercise.

A firm uses its beliefs about the merits of alternatives as the basis upon which it makes decisions. For instance, in a financial option setting, it is trivial to compare the strike price of an option with the market price at a given point in time (look at a Reuters terminal and do the simple subtraction). In contrast, in a real option, the firm must compare its beliefs about the value of the project with its beliefs about the strike price associated with exercising the option. As a consequence, at the exercise time, the appropriate decision is ambiguous.

Specifically, one can, in an abstract sense, think of a firm as having a decision rule that maps its beliefs about the merits of the actions to specific choices (Posen and Levinthal 2012). A firm may make erroneous decisions either because its beliefs are inaccurate or because it does not act appropriately on those beliefs. Ceteris paribus, more accurate beliefs are likely to lead to better decisions. However, a firm may not act optimally on its beliefs. For instance, Guler (2007) finds that venture capital firms do not terminate underperforming portfolio companies at the optimal time (they wait too long), and she attributes this to behavioral rather than informational problems. This inability to act on beliefs may result from, for example, risk aversion (Kahneman and Tversky 1979), status quo bias (Samuelson and Zeckhauser 1988) and escalation of commitment (Staw 1981). It may also arise from a purposeful choice to trade-off exploitation and exploration across multiple time periods (March 1991).

Second, in a learning model, a firm updates its beliefs about the merits of its choice alternatives as it gathers additional information, often by making decisions and observing the results. However, this new information is often ambiguous (March and Olsen 1975). For instance, an investment in a prototype production facility may indicate high production efficiency, but this may not be representative of the efficiency of a larger facility. We use the term evaluative uncertainty to refer to this informational challenge (Knudsen and Levinthal 2007). It arises because stochastic processes (e.g., competition), complexity (Levinthal 1997), and causal ambiguity (Lippman and Rumelt 1982; Ryall, 2009) give rise to noisy signals that make the evaluation of feedback challenging (Knudsen and Levinthal 2007).

A firm uses this new information, even though it is subject to evaluative uncertainty, to update its beliefs about the merits of alternatives. In the absence of evaluative uncertainty, belief updating is simple. After the perfectly informative new information is received, beliefs are updated to fully incorporate the new information. For instance, assume a phone developer believed that rectangular and square smartphones were best with a fifty percent weighting on each. Assume that the firm invests in a large focus group that would (wonderfully) provide a definitive answer —rectangular or square phone design. If the answer is rectangular, then the firm would (rationally) update its beliefs to rectangular (with a 100 percent weighting, and square with a 0 percent weighting).

In the presence of evaluative uncertainty, the belief updating process is challenging. Theories of adaptive rationality assume Bayesian updating — belief updating that is adaptively rational in that it appropriately accounts for the noisiness of the feedback in the sense that it is informationally efficient (e.g., Posen and Levinthal 2012).[6] Updating beliefs at a rate lower than optimal reflect underweighting of the information in the noisy signal, while updating beliefs faster than optimal reflects overweighting of the information in the noisy signal. Non-rational (e.g., non-Bayesian) updating of beliefs in the face of evaluative uncertainty may result from factors such as managerial over-confidence (e.g., Camerer and Lovallo 1999) and hubris (e.g., Hiller and Hambrick 2005). Deviations from adaptive rationality, when there is evaluative uncertainty, gives rise to biased beliefs about the merits of the action and, as a consequence, erroneous decisions.

*Implications of a Learning Model for Real Options*

The *evaluative uncertainty* that is central to learning theory differs from *project uncertainty* that is central to real options theory. Project uncertainty is forward looking from the time the firm first considers purchasing an option. While it may be endogenous or exogenous, it is about the inherently unpredictable future state of the world. If a residential building firm takes an option on a parcel of rural property, it may be concerned about project uncertainty that arises because the property must be rezoned for residential use. There is inherent uncertainty regarding the outcome of rezoning, perhaps depending on the outcome of a local election. But this uncertainty is unambiguously resolved at some point in time — the zoning status is, or is not, amended to permit residential use. Yet in many, and perhaps most, firm investment decisions, the firm does not receive a yes-no signal that resolves uncertainty.

Consider a pharmaceutical firm developing a new drug. It may engage in a phase 3 clinical trial that will take one year to complete. This investment can be seen as an option on commercializing the drug if the outcome of the phase 3 trial is successful. The phase 3 clinical trial reflects a deferral option: the option to defer further investment until project uncertainty is resolved (Leiblein and Ziedonis 2007). After completing the Phase 3 clinical trial, the firm analyzes the data, engaging in statistical tests to understand both the efficacy of the drug, and its side effects. Yet the results are complicated, clouded in

[6] In this study, rational behavior implies belief updating reflects estimation that maximizes the posterior expectation of a utility function (Lehmann and Casella 1998).

ambiguity. While *project uncertainty* associated with this clinical trial will have been resolved with the completion of the phase 3 clinical trial, there is still substantial *evaluative uncertainty* because the data on efficacy and side effects must be mapped to the future profit potential of the drug.

Consider all of the key parameters that are needed to employ real options theory in practice: cost of the initial investment (C), strike price at which the firm can exercise the option (K), project uncertainty (σ), value of the project if fully invested at t=0 ($S_0$), and value of the project at exercise time ($S_1$). The traditional real options literature assumes that managers have accurate and timely information on of these parameters. In reality, they are not likely to have accurate information on any of these parameters. Rather, they have beliefs about each of them — beliefs that may be more or less accurate.

In this paper, we focus on one parameter alone, the value of the project at exercise time ($S_1$). We leave to subsequent research the implications of relaxing assumptions about the other parameters.

As such, in the pharmaceutical example, we assume that the firm "knows" with certainty at t=0 the following: cost of the phase 3 trial (C), cost of subsequent commercialization (K), and the value of the drug if it fully committed at t=0 to all future development and marketing of the drug ($S_0$).

In this pharmaceutical example, only the value of the project after the completion of the phase 3 trial ($S_1$) is not fully known. Instead, the firm has some initial belief at t=0 about the value of the project at t=1. We can write the initial belief, in log form, as:

$$b_0 = g(s_1) \qquad (7)$$

where $s_1$ is the log true but latent value of the project at t=1, and $b_0$ is the firm's belief about $s_1$. g(.) is a function that modifies the correlation between beliefs and reality about $s_1$ — the possibility that the firm's beliefs do not accurately reflect the true value. Because the expected value of $S_1$ is $S_0$ in the Black-Scholes formulation (Equation 4), we assume that $b_0 = s_0$. That is, the firm's initial belief about the value of the project at t=1 is the expected value of the project at *t*=1.

In the pharmaceutical example, the firm knows with relative certainty the cost to purchase the option (cost of running the phase 3 trial), C, as well as the exercise price (cost of commercialization), K, and the level of project uncertainty, σ.

To assess the value of this deferral option, the firm calculates the option value according to the Black Scholes formulation. If the Black-Scholes option value is C* (Equation 6), the firm would be willing to proceed and invest in the option if C < C*. In the classic real options tradition, the calculation of the value of the real option, C*, and the decision to execute the option if the project is worth more than the strike price, $S_1 > K$ (or equivalently in logs, if $s_1 > k$), is trivial. However, in a learning context with evaluative uncertainty, the firm does not know $s_1$. Rather, the firm has a belief, $b_1$, that may be more or less accurate.

We consider the implications of behavioral and informational challenges for the value of an option, and assess the implications for the real value of the option that appropriately accounts for behavioral and informational deviations from the real options assumptions. In doing so, we develop a behavioral theory of real options.

After paying for the option, and at the conclusion of the phase 3 trial in one year, the firm will have to decide whether or not to exercise the option by investing to commercialize the drug. This process is influenced by both project uncertainty and evaluative uncertainty, as well as the efficacy of the firm's belief updating process. We modify the Black-Scholes formulation of project uncertainty as geometric Brownian motion, in the log formulation of Equation 4b, as follows:

$$\hat{s}_1 = s_0 + r_{rf} - \sigma^2/2 + \sigma v + n \tag{8}$$

where σ is the project uncertainty, per the Black-Scholes formulation, and n is a mean zero gaussian disturbance term for evaluative uncertainty, per a bandit model (e.g., Posen and Levinthal 2012). The remaining parameters follow the earlier Black-Scholes discussion. As a consequence, rather than observing $s_1$ at the exercise time, the firm observes $\hat{s}_1$, because of evaluative uncertainty, n, that is normally distributed (with mean zero, and some variance). Equation 8 reduces to the standard gaussian Bandit model of learning under uncertainty when $\sigma=0$.

A firm acting in an adaptively rational manner would not fully update its beliefs to $S_1$ because the firm is assumed to know that the $\hat{S}_1$ it observes is, in part, the subject to a stationary stochastic process of evaluative uncertainty, n. In particular, if there is evaluative uncertainty, $n > 0$, then an adaptively rational firm will not update fully. Instead, belief updating will reflect partial adjustment of beliefs to the new information (Lave and March 1971, Bush and Mosteller 1955). As such, the firm's belief after the new information is defined by:

$$b_1 = (1 - \alpha)b_0 + \alpha\hat{s}_1, \tag{9}$$

where $\alpha$ is the rate of fractional updating of beliefs. Equation 9 suggests that the updated belief reflects a mixture of the initial belief $b_0$ and the new information $\hat{s}_1$. Because Equation 8 takes the form of a standard Gaussian bandit model (when σ=0), we do belief updating in logs rather than levels.

This formulation of belief updating is flexible. α may be set such that the firm is adaptively rational, but this need not be the case. The adaptively rational learner, by definition, makes maximal use of new information. If the data is free of noise, n=0, then it is optimal to fully update at α=1. If there is evaluative uncertainty, then the optimal updating rate is α<1. The optimal α, which we label α*, is calculable. In a derivation, available from the authors upon request, we find that α* depends not only on the level of evaluative uncertainty, but also the level of project uncertainty.

A key feature of our behavioral model of real options is that it incorporates both evaluative uncertainty and behavioral deviations from adaptive rationality — and it nests the Black-Scholes model. The model reduces to the Black-Scholes model of real options investment under uncertainty (Black and Scholes 1973) in the corner of parameter space defined by the absence of evaluative uncertainty, n=0, and adaptively rational belief updating, α=α*. Likewise, the model reduces to the Bandit model of learning under uncertainty (Gittins 1979, Denrell and March 2001, Posen and Levinthal 2012) in the corner of parameter space defined by the absence of project uncertainty, σ=0. The model described above is solvable through computational techniques that are amenable to managerial calculation using standard spreadsheet technologies.

At the exercise time, in a context of behavioral and informational conditions that deviate from the assumptions of financial markets and rationality, the firm makes its exercise decision on a comparison of its beliefs about the value of the project at t=1 relative to the strike price. That is, the firm exercises the option if $B_1 > K$ (or equivalently, $b_1 > k$), and terminates the project if $B_1 < K$. The firm's believes, $B_1$, may deviate from the true, but latent, value, $S_1$, because of evaluative uncertainty, n, and belief updating that is not adaptively rational (α ≠ α*). As a consequence, a firm may make systematic errors in choosing to either exercise or terminate the option. If the firm exercises the option because $B_1 > K$, but in reality $S_1 < K$, then the firm will be making an error of over-investment — exercising the option when it is not in the money. In contrast, if the firm terminates the option because $B_1 < K$, but in reality $S_1 > K$, then the firm will be making an error of under-investment — failing to exercise the option, when it is in the money. These errors lead to what we call regret, which we define as the loss associated with informational and behavioral deviations from the assumptions of financial options.

Our behavioral model of real options suggests option values that are always lower than the

Black-Scholes. That is, as long as there are informational or behavioral deviations from rationality, regret is always positive, indicating losses relative to the Black-Scholes estimate of the value of flexibility inherent in the option.

In sum, evaluative uncertainty makes learning difficult. We believe that the prior literature has confounded the two sources of uncertainty, project uncertainty and evaluative uncertainty. This observation may explain why van Putten and MacMillan (2004) argue that there is a "flee zone" where high uncertainty makes the real options approach untenable (uncertainty is typically assumed to increase option value). We believe that most real options contain both project and evaluative uncertainty, and the evaluative uncertainty makes behavioral deviations from rationality likely. Our derivation of behavioral real options suggests that the value of an option is increasing in project uncertainty (as standard option intuition suggests), but is decreasing in evaluative uncertainty. As a consequence, our theory predicts what van Putten and MacMillan (2004) observe: managers applying the real options approach tend to "overestimate the value of uncertain projects, encouraging companies to overinvest in them".

In the next section, we exercise the model of behavioral real options, across informational and behavioral deviations from the assumptions of financial options. We do so in order to demonstrate that the model can generate the Black-Scholes solution for the value of an option — i.e., the value of flexibility. We then show that informational and behavioral deviations from the financial options assumptions reduce the value of flexibility, and decompose the reduced value into that resulting from over-investment versus under-investment.

**4. Simulation Model and Results**

We simulate and analyze the effects of evaluative uncertainty and limited rationality on option value. Since our model embodies the Black-Scholes financial options solution as a special case, our approach is to take this as a baseline and systematically relax the Black-Scholes assumptions as shown in Table 1.

<< Insert Table 1 about here >>

*Simulation Model*

In our analysis we use Monte Carlo simulation to capture three central features of our real real options framework: movement in the underlying asset, belief formation, and the decision on whether to exercise. The simulation comprises $N = 5,000,000$ trials, where each trial consists of the following three steps. The first step defines the movement in the underlying asset, defined in Equation 8, from its initial value, $s_0$, to the updated value after project uncertainty is resolved, $s_1$. This movement is governed by a random walk in the form of geometric Brownian motion, per the Black-Scholes formulation, as well as a mean zero gaussian disturbance term for evaluative uncertainty, per a bandit model (e.g., Posen and Levinthal 2012). Implementing Equation 8 requires choosing values for the parameters $S_0$, $K$, $r_{rf}$, σ, α, and the variance of the disturbance term n, which are stable across all trials). Then, we take a random draw of $v$ (corresponding to project uncertainty) and $n$ (corresponding to evaluative uncertainty), and apply Equation 8 to obtain the value of $\hat{s_1}$ for the trial. The second step captures the belief updating process as defined by Equation 9, using the value of $\hat{s_1}$ obtained in step 1 to compute the decision-maker's belief, $b_1$, on the underlying asset price (in log terms). Finally, we determine whether the decision-maker will exercise the option. The decision-maker exercises the option if $B_1 > K$ (or alternatively, $b_1 > k$) in which case the payoff to the option (value of flexibility) is $(S_1 - K)/(1 + r_{rf})$, reduced by the price paid for the option, C. The decision-maker terminates the project if $B_1 < K$, in which case the option value has a 0 payoff, and the total return is $-C$. Since $B_1$ may differ from the true asset price, $S_1$, the decision-maker may make errors in its exercise decision leading to under- or over-investment.

In the presentation of our results below, we examine the value of a real option across levels of project uncertainty, σ, on the range [0, 1]. We define the level of evaluative uncertainty as a share of project uncertainty, represented by the evaluative uncertainty coefficient, $\lambda$. For example, if σ=0.5, and λ=0.5, the standard deviation of evaluative uncertainty is 0.25. We use the extent of project uncertainty and evaluative uncertainty to define the optimal rate of belief updating in Equation 9. In particular, we compute the optimal (rational) rate of belief updating, which we define as $\alpha = \alpha^*$. Since $\alpha^*$ is a function of the parameters employed in the options model, it is computed by running the basic simulation across α from 0 to 1 in small increments, and setting $\alpha^*$ to the α that maximizes the sample average of option payoff (as defined above). After determining $\alpha^*$ in this fashion, non-rational behavior simply means that a decision-maker updates at a fractional updating rate α different from $\alpha^*$. For example, a decision-maker may update at a rate α that is half of optimal, which we write as $\alpha = 0.5\alpha^*$.

<< Insert Table 2 about here >>

The parameter settings, used in the generation of the results below are described in Table 2.

Parameter values are chosen to simplify exposition. For example, we set $I_0 = 0$ and $F_1 = 1$, which results in a project value of $S_0 = 1$, when project uncertainty is σ=0. The strike price is chosen as a sensible value in exponential space, reflecting the fact that, in our model, beliefs are formed in logs. We set $K = e^{0.25} = 1.28$ so that the strike price is a reasonable level above the initial stock price $S_0 = e^0 = 1$. Finally, the values we use for discounting, $r_{rf}$ and $r_{dcf}$, which are not central to the analysis in this paper, were set to $r_{dcf} = 0.3\,\sigma$ and $r_{rf} = 0$, implicitly assuming a zero risk free rate.[7]

*Experiment 1: Effect of Evaluative Uncertainty on (Black-Scholes) Option Value*

In our first experiment, we examine the impact of evaluative uncertainty on the value of flexibility in a single period option. The main idea we seek to illustrate is that, for adaptively rational decision-makers, evaluative uncertainty erodes the value of flexibility.

Figure 2 decomposes project value $P$ into that contributed by DCF logic and that contributed by option value, for three levels of evaluative uncertainty corresponding to λ = 0, 0.5, and 1. In this experiment, decision-makers are adaptively rational, updating beliefs at the optimal fractional updating rate α*.

<< Insert Figure 2 about here >>

Two central implications are illustrated in Figure 2. First, the figure illustrates that as project uncertainty σ increases, DCF value declines but option value increases. Greater project uncertainty implies riskier cash flows, which increases the risk (denominator) embodied in the DCF calculation. But because greater project uncertainty also implies a wider dispersion in project values, the value of flexibility (i.e., option value) increases. Second, the value of flexibility decreases with evaluative uncertainty. In particular, the dotted line corresponds to the Black-Scholes option value that would be generated in an informationally perfect world without evaluative uncertainty. As evaluative uncertainty λ increases (diamond and + markered lines), the option value declines across all levels of project uncertainty σ, with a larger decline as σ increases.

Why does evaluative uncertainty erode option value? At a basic level, evaluative uncertainty leads

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[7] The results are qualitatively robust to different settings of the discount rate. Under DCF logic, $r_{dcf}$ reflects the risk of future cash flows forecasted in the current period. A incremental product-line extension, for example, implies the use of a standard firm-level cost of capital (e.g., weighted average cost of capital) in the range of, say, 0.05 to 0.3. For the purposes of analysis, we extend this range to include the extreme of riskless future cash flow (i.e., $r_{dcf} = 0$), which leads to $r_{dcf} = 0.3\sigma$ (we limit σ to [0,1] in our results).

to regret, wherein decision-makers make mistakes in exercising an option (i.e., mistakes they regret because value is destroyed). Decision-makers act on beliefs regarding the value of the project at time=1 and may under-invest by not exercising an option when profitable to do so or over-invest by exercising an option when not profitable to do so.

<< Insert Figure 3 about here >>

In Figure 3, we hold the evaluative uncertainty coefficient constant at $\lambda = 0.5$ and decompose regret into the contributions from under-investment and over-investment. This is readily accomplished in our Monte-Carlo simulation by classifying each individual random trial as an under- or over-investment error. Under-investment errors occur when the belief, $B_1$, is below the exercise price, $K$, but the actual project value, $S_1$ is above $K$. Over-investment errors occur when the belief, $B_1$, is above the exercise price, $K$, but the actual project value, $S_1$ is below $K$. Since decision-makers are rational, regret is purely evaluative (that is, due to evaluative uncertainty) rather than behavioral. As Figure 3a indicates, under-investment is a bigger challenge for the decision-maker than is over-investment (for the given parameters). Figures 3b and 3c delve into this further by examining the frequency and size of the under- and over-investment errors that underlie regret. We find that at low levels of project uncertainty, regret is driven by the larger number of under-investment errors, while at higher levels of project uncertainty, regret is driven by the larger error magnitude of under-investment events.

*Experiment 2: Effect of Limited Rationality on (Black-Scholes) Option Value*

In Experiment 2, we examine the effects of limited rationality on the value of flexibility in a single period option, but exclude issues of evaluative uncertainty that we discussed in Experiment 1 (i.e., we set $\lambda=0$). All parameter settings for Experiment 2 are the same as those in Experiment 1 (see Table 2), except that we allow non-rational behavior in the sense that we examine the option value for fractional updating rates $\alpha < \alpha^*$. As we demonstrate below, non-rational behavior erodes the value of flexibility under options logic.

The simulation results, depicted in Figure 4, show that the value of flexibility (i.e., option value) erodes with limited rationality. Once again, we show the DCF value of the project in the lower panel, the value of which is unaffected by rationality in belief updating. The o-markered line corresponds to decision-making with no evaluative uncertainty, so it is the Black-Scholes option value. As behavior becomes increasingly non-rational (diamond and + markered lines), option value declines at all levels of project uncertainty $\sigma$, which reflects the fact that non-rational decision-makers make more exercise errors. Note also that the decline is larger as σ increases.

<< Insert Figure 4 about here >>

In Figure 5, we now turn to a closer examination of how limited rationality erodes option value by inducing regret — that is, by causing exercise errors. Since there is no evaluative uncertainty, regret is purely behavioral. We decompose this behavioral regret into the contributions from under- and over-investment with the non-optimal fractional updating rate fixed at $\alpha = 0.5\alpha^*$. As Figure 5a indicates, regret is purely from under-investment, as expected since the optimal rate of updating is full and immediate (i.e., $\alpha = \alpha^* = 1$). Figures 5b and 5c show the frequency and size of the under- and over-investment errors that lead to regret. The rate of error grows rapidly, but stabilizes at around σ=0.4. The magnitude of errors grows continuously with project uncertainty, which is expected because of the larger potential performance extremes associated with higher project uncertainty.

<< Insert Figure 5 about here >>

*Experiment 3: Joint Effects of Limited Rationality and Evaluative Uncertainty on Option Value*

In this experiment, we employ a mixed model in that we relax both full information (i.e., no evaluative uncertainty) and rationality (i.e., rational belief updating) assumptions of a Black-Scholes options model. Figure 6 shows that pure evaluative uncertainty erodes option value (diamond-markered line), and adding non-rational belief updating on top of this further erodes option value. Moreover, option value continues to decreases as a decision-maker diverges more from rational adaptive learning.

<< Insert Figure 6 about here >>

In Experiments 1 and 2, decline in option value was due solely to evaluative uncertainty and limited rationality, respectively. In this experiment, both forms of decline contribute to regret. As such, in Figure 7 we decompose regret into that due to evaluative uncertainty and that due to limited rationality. Mechanically, the decomposition is computed by considering three payoff values: $P_1$, the Black-Scholes payoff, $P_2$, the Bayesian payoff with evaluative uncertainty ($\lambda = 0.5$), and $P_3$, the payoff with non-Bayesian ($\alpha = 0.75\alpha^*$) behavior and evaluative uncertainty ($\lambda = 0.5$). $P_1 - P_3$ is interpreted as total regret, $P_1 - P_2$ as evaluative regret, and $P_2 - P_3$ as behavioral regret.

<< Insert Figure 7 and 8 about here >>

Figure 7 shows that evaluative regret is more problematic at all levels of project uncertainty. Notice that total regret in this mixed model is approximately the superposition of the purely evaluative (Figure 3a) and purely behavioral (Figure 5a) regret models. That is, the level of behavioral regret in the mixed model is approximately that in the model with only behavioral regret, and the level of evaluative regret is approximately that in the model with only evaluative regret.

As in the prior experiments, regret may also be decomposed into under- and over-investment components, as given in Figure 8. Figure 8a shows that under-investment is a much larger contributor to regret than is over-investment. Unlike the evaluative-behavioral decomposition in Figure 7, the levels of under- and over-investment regret do not reflect the superposition of the purely evaluative and purely behavioral models.

The total over-investment regret from the model with purely evaluative regret (Figure 3a) is approximately consistent with over-investment regret in this model that jointly has informational and behavioral deviations (Figure 8a). In contrast, the level of under-investment regret is magnified in this model that employs both informational and behavioral deviations from the traditional real options assumptions. That is, at $\sigma=0$, under-investment regret is approximately 0.04 (Figure 8a). The under-investment regret in the informational deviation model (Figure 3a) is 0.02 and the behavioral deviation model (Figure 5a) is 0.01. A comparison of Figure 3b/c with Figure 8b/c suggests this is due to a reduction in both the frequency and size of over-investment errors, though the frequency reduction seems the larger effect. Intuitively, we would expect this interaction between evaluative uncertainty and limited rationality — since the non-rational decision-maker is "conservative" in the sense of updating less aggressively to new information than is optimal, there should be a reduction in over-investment relative to the rational decision-maker. Thus, this result suggests that non-rational belief updating (at a sub-optimal rate) may offset some of the over-investment error that arises from evaluative uncertainty.

## 5. Discussion

In this paper we set out to develop and propose new theory that describes how informational properties of the environment and behavioral properties of firms influence strategic investment decisions when there is substantial uncertainty about future returns — e.g., building a new production facility, developing a new technology, or entering a new country. The standard logic used to evaluate such decisions is predicated on economic models from finance theory (e.g., Brealey, Myers, and Allen 2010). The past two decades, however, have witnessed substantial changes in the way scholars think about how uncertainty impacts strategic decisions. Whereas the traditional DCF approach indicates that the overall value of a particular investment declines as uncertainty increases, the real options approach identifies how a component of project value, option value, increases with uncertainty. These approaches lead to differing conclusions because real options takes seriously the role of managers. If a manager can respond flexibly to new information, making a smaller investment today that provides a preferential claim on the opportunity to make additional investments in the future, then the firm may exploit uncertainty, rather than avoid it.

While the theory of real options has its roots in finance (e.g., Myers 1979), it has been of broad appeal to strategy scholars. Early theoretical contributions include Bowman and Hurry (1993), Kester (1984), and Kogut (1991). Real options logic has been used to predict a multitude of managerial investment behaviors including: entry into an industry (O'Brien, Folta, and Johnson 2003, Raffiee and Feng 2014), investment in capabilities (Kogut and Kulatilaka 2001; McGrath, 1997; McGrath and Nerkar, 2004), venture capital investments (Li and Chi 2013), make or buy (outsourcing) decisions (Leiblein and Miller, 2002), international alliances and diversification investments (Reuer and Leiblein, 2000; Reuer and Tong 2010), and acquisitions (Chi, 2000). Indeed, it may be fair to say that good managers must act as “naive option-takers”, employing an intuitive understanding of the value of flexibility, even in the absence of a deep understanding of the mathematics of Black-Scholes (1973).

Despite the intuitive appeal of real options, its strong theoretical grounding, relatively easy application, and substantial positive press (Courtney, Kirkland, and Viguerie, 1997; Coy, 1999; Luehrman, 1998), anecdotal evidence suggests that in many circumstances, the value of flexibility is ignored in the decision making process (Teach 2003). Even proponents of real options logic have come to articulate conditions under which managers should avoid the approach (van Putten and MacMillan 2004) because they are likely to “overestimate the value of uncertain projects, encouraging companies to overinvest in them”. Conditions that lead managers to systematically overlook or overestimate the value of flexibility are likely to have significant implications for a key question in strategy: why firms differ in their activities, capabilities, and performance (e.g., Rumelt, Schendel, and Teece, 1991, 1994).

The analysis presented here suggests that the slow diffusion of real options in practice, and erroneous decisions that may result from its implementation, may be at least partially addressed by joining the real options model with an experiential learning model. Both models provide explanations of sequential decision making processes under uncertainty, however, they make different assumptions regarding the sources of uncertainty and the rationality of the decision-maker. Whereas the real options model emphasizes project uncertainty and rational decision-making, the behavioral learning model emphasizes evaluative uncertainty and boundedly rational decision-making. Project uncertainty is uncertainty about the state of future cash flows. In contrast, evaluative uncertainty reflects the real informational challenge that arises because stochastic processes (e.g., competition), complexity (Levinthal 1997), and causal ambiguity (Lippman and Rumelt 1982; Ryall, 2009) give rise to noisy signals that make the evaluation of feedback challenging (Knudsen and Levinthal 2007). As such, evaluative uncertainty arises in real options, but not in financial options, because the former does not have spot markets that provide unambiguous prices (e.g., on a Reuters terminal).

This paper develops a model that incorporates the value of flexibility in response to project uncertainty highlighted by real option theory, as well as the influence of evaluative uncertainty and bounded rationality highlighted by behavioral learning theory. Our model nests the Black-Scholes result — if evaluative uncertainty is absent and the decision-maker is rational, the result of our model converges Black-Scholes. To our knowledge, this study is the first attempt to model the joint effect of evaluative and project uncertainty on project valuation and investment decisions.

*Main Findings*

Our model suggests three main findings. First, we demonstrate that the classic association between project riskiness (i.e., project uncertainty), the DCF component of valuation, and the real option component of valuation, are sensitive to assumptions regarding the informational environment within which managers act. More specifically, we recognize that these canonical associations only hold in environments characterized by unambiguous information and rational decision making. Relaxing assumptions about the informational environment leads to a notable decline in the real option component of a valuation. That is, evaluative uncertainty decreases the value of flexibility. This is an exciting finding that provides an explanation for claims by practitioners that standard application of option logic leads to over-investment. This finding also speaks directly to the benefits of linking economic and behavioral approaches to firm strategy. In particular, as expanded on below, this finding highlights important interdependencies between rigorous economic principles regarding project valuation and well-understood behavioral principles regarding how organizations actually work.

Second, the presence of evaluative uncertainty suggests a source of systematic error in investment decisions predicated on leveraging the value of flexibility. These erroneous decisions underlie the decline in real option value discussed above. We decompose declines in the real option component of value into errors of under-investment (failing to exercise an option that is "in the money") and over-investment (exercising an option that is "out of the money"). The model suggests that, holding fixed the extent of evaluative uncertainty (as a share of project uncertainty) under-investment may be a bigger challenge than is over-investment — and the extent of the value decline is increasing in project uncertainty. We also observe that differences in the probability of under- and over-investment, and their average magnitudes, vary across project uncertainty. Over-investment errors become more likely at higher levels of project uncertainty, relative to under-investment errors, even though they decline in average magnitude. This finding resonates with work in the empirical real options literature on project entry (e.g., Kulatilaka and Perotti, 1988; Folta and O'Brien, 2004). For instance, Folta and O'Brien (2004) find a non-monotonic effect of uncertainty on entry that results from differential uncertainty in the option to defer versus grow. Our result points to a different contrast — uncertainty experienced by managers in the real world includes both project uncertainty and evaluative uncertainty, and the joint effect may explain why, when these two forms of uncertainty are high, managers may tend to either avoid investing altogether, or under-invest at exercise time.

Finally, building on the large research literature on behavioral deviations from rationality, our model further and specifically demonstrates how bounded rationality impacts the value of flexibility. Managers may learn more slowly than would a "rational" manager, a behavior that would be consistent with risk-aversion, managerial hubris, or the existence of firm-level systems that inhibit updating of the firm's initial prior. When this occurs, the value of the real option diminishes rapidly. The diminished value results from under-investment errors (managers fail to exercise in-the-money options). This problem is further compounded when there is both evaluative uncertainty and bounded rationality. Errors of under-investment dominate errors of over-investment, both in the probability of occurring and in their average magnitude.

Consider the well-known example of Xerox's PARC Laboratory, which is famous for inventing, but failing to commercialize, many elements of the modern computing ecosystem. The initial investment can be viewed as the pursuit of an option to explore and (potentially) commercialize emerging technologies. Xerox succeeded in the exploration phase but failed to exercise the option. In real options theory, firms don't make errors at exercise time and the value of the option is increasing in project uncertainty. In our model, the value of the option is increasing in project uncertainty but declining in evaluative uncertainty and non-rational behavior because beliefs about the merits of exercising the option may deviate from the latent value of doing so. It is clear that Xerox faced not only project uncertainty but also evaluative uncertainty. Whether the computer mouse would diffuse is a question of project uncertainty. But there is also substantial evaluative uncertainty. That is, while there existed some true probability, $p$, regarding the success of the computer mouse, Xerox managers could not look at a Reuters terminal with spot market prices to observe that probability. Rather, Xerox managers observed a noisy estimate $p+\varepsilon$, and made their commercialization decision on that basis. Doing so naturally leads to errors, which our model suggests tend towards under-investment.

*Limitations*

The results we present in this paper are, at best, an incomplete sampling of the ways in which firms, employing real options to evaluate investment decisions under uncertainty, may deviate from the rational benchmark of Black-Scholes. As a consequence, there are several limitations worth mentioning, many of which are the subject of our ongoing research to be included in subsequent papers. First, we examine the implications of evaluative uncertainty about the value of the project at exercise time. One could also consider the implications of uncertainty about the initial value of the project, or the extent of project uncertainty. Evaluative uncertainty on these parameters may have very different implications for the types of investment decision errors that may arise. Second, we have taken the option cost and exercise price as given, an assumption that is common in textbook-type examples of the application of real options (e.g., Borison 2005). But for a given level of uncertainty, there are many choices of option price—exercise price pairs. If a firm wants to take a lower up front option price, it must accept a higher exercise price. Our preliminary analysis suggests that firms may be able to shift the balance between errors of over- versus under-investment by shifting the option and exercise prices. If there are contexts where one form of error or the other is more costly, then a further examination of this possibility may generate important insights. Finally, there are a variety of other behavioral issues, including risk aversion and framing (see Coff and Laverty, 2007) that are likely to influence real-world option valuation, the actual exercise of options, and sequential decision-making. Extending the present analysis to incorporate these effects may yield novel insights.

*Implications*

Overall, these results suggest that research that fails to acknowledge informative and behavioral realities of firms may generate misleading conclusions about the value of flexibility inherent in taking an options perspective on resource allocation. Of course, most strategy scholars would find that conclusion to be self-evident — deviations from rationality lead to outcomes that are inferior to rational optimization. Our contribution lays in the formal logic of our approach that links real options theory to behavioral learning theory. Our approach to real real options is amenable to actual calculations by managers. More importantly, our approach produces formal predictions about the types of errors — over- versus under-investment — that are likely to occur. This in turn paves the way for empirical work regarding the comparative influence of informational and behavioral deviations from rational assumptions for firm investment behavior and competitive heterogeneity.

These results have important implications for future development of real option theory in the strategy literature. It has been over a decade since the substantial debate on the merits of the real options approach appeared in the pages of the Academy of Management Review (Adner and Levinthal, 2004a, 2004b; Kogut and Kulatilaka, 2004; McGrath, Ferrier, and Mendelow, 2004). Our theorizing, which highlights the implications of evaluative uncertainty and deviations from behavioral rationality, casts new light on this debate. In our view, the authors were talking past one another, in part because, at that time, there were no formal tools to enable disentangling of the set of interdependent issues associated with the challenges of translating formal real options logic to the real-world.

Kogut and Kulatilaka (2004) and McGrath, Ferrier, and Mendelow (2004) focus on behavioral deviations from the rationality assumptions in formal real options theory. They accept that deviations from rationality occur, but argue that the magnitude of the issue is limited, and tend to assume that organizational heuristics may counter these biases. In contrast, Adner and Levinthal (2004a) focus on informational challenges associated with evaluative uncertainty. In their rebuttal, Adner and Levinthal (2004b p.121), argue that the "issues we raise are not artifacts of individual biases in decision making.... Such deviations from rational choice accentuate the problems we raise but are not their root cause." Instead, they point to a wide array of informational challenges such that "even well-motivated intentionally rational organizations will confront difficulties in the efficient abandonment of opportunities".

While our model does not "resolve" the AMR debate, it does help us to better understand the basis for the discussion in a manner that takes seriously the informational and behavioral challenges of the real-world. Our theory, which adds behavioral learning elements to the rational decision-making of real options, allows us to model the interaction of informational and behavioral issues. The theoretical benefits of flexibility emphasized in the option logic remain intact. But the extent to which these benefits are achievable by firms is still open to question. There is no definitive, overarching answer. Rather, our model helps us to understand the conditions under which one challenge or the other binds, and how the benefits of flexibility are eroded, as firms seek to exploit, rather than avoid, uncertainty in the real-world.

The model we develop has implications for research in the management literature on learning. It is fair to say that the learning literature, with its roots in the Carnegie School, has had a substantial impact on research in strategy. While learning theory makes predictions that are consistent with managerial behavior, the formal models employed in the literature have often been criticized (e.g., March 1991, Levinthal 1997, Denrell and March 2001, Posen and Levinthal 2012) as excessively abstract representations that are challenging to translate into real managerial settings. In contrast, the model we develop, which integrates a Bandit model of learning with the Black-Scholes real options model, is concrete. Our model makes specific predictions about the types of errors (over- versus under-investment) and their magnitudes in dollar terms. Moreover, it is a hallmark of research in the Carnegie tradition that theory employs realistic behavioral and informational assumptions — our model does so, but goes far beyond prior work on learning in management, because our model enables the formal (dollar) pricing of the value associated with firms' attempts to exploit uncertainty.

The above insights also present several opportunities for future management and strategy research to integrate other aspects of managerial behavior and organizational design into the model. The paper suggests reasons to investigate new sources of competitive heterogeneity. Specifically, the paper provides a method to consider the extent to which heterogeneity comes from differences in beliefs (and learning) as compared to differences in information. Whereas economically based strategy tools allow us to consider how differential endowments (Barney, 1991), information asymmetry (Barney, 1986), or factor market failures (Lippman and Rumelt, 1982) may generate competitive heterogeneity, these tools do not provide an explanation for sources of heterogeneity in beliefs. By demonstrating how the resource allocation process (Bower, 1970; Maritan, 2001) is affected by differences in evaluative uncertainty and/or behavioral rationality, this paper suggests a means for research to explore and compare these two sources of heterogeneity. Demonstrating how project and evaluative uncertainty, as well as rationality, affect investment behavior also has implications for understanding why firms differ in their ability to reduce evaluative uncertainty and "sense" valuable opportunities, consider the strength of claims on a sequence of investments and "seize" opportunities, or use probing, option like investments to "transform" an organization (Teece, 2007). This is a particularly important avenue for future work as we can have no deep understanding about average, systematic, differences in behavior without an understanding of the differences in heterogeneity in beliefs.

The discussion of evaluative uncertainty and the relative rationality of decision-makers also has implications for scholars interested in the decision-making processes of top managers. Our model provides a means to explain and test whether and how top decision-makers contribute to firm value (e.g., Mackey, 2008). For example, in 2008, the decision-making teams at Apple and Research in Motion faced similar levels of project uncertainty regarding the payoffs to the development of the next generation smartphone. However, differences in beliefs and the ability to process that information may have led to observed differences in resource allocation. One may consider, for example, differences across firms in: the cognitive ability of the decision-making team (e.g., Davis, Eisenhardt, and Bingham, 2009; Felin and Foss, 2005; Foss, 2011; Gavetti and Levinthal, 2000), problem formulation processes (e.g., Baer, Dirks, and Nickerson, 2012; Nickerson, Yen, and Mahoney, 2012), or problem solving processes (e.g., Nickerson and Zenger, 2004) that allow organizations to "see through the mist" of volatile decisions and more accurately allocate resources to investment trajectories. This suggests the possibility for future empirical work to contribute by testing whether, and to what extent, the selection of managers with particular characteristics or the use of particular organizational mechanisms impacts subsequent resource allocation decisions.

The results also have interesting managerial implications. Anecdotal evidence suggests that DCF is still the dominant tool by which managers evaluate investment decisions. Of course, the DCF approach implies that the larger the level of uncertainty the lower the likelihood of investment. In contrast, the standard application of real options logic provides a rationale for greater investment under uncertainty because managers have the ability to respond flexibly to new information. Our model suggests that the limited adoption of real options in practice (Teach 2003) may not reflect managers unwillingness to adopt the real options toolkit, or a limited managerial valuation of flexibility, but rather, a quite rational avoidance of a tool that is functional in the world of financial options, but is significantly less functional in the real world. Indeed, even proponents of real options advise managers of the need to "flee" from projects where there are very high levels of uncertainty (van Putten & MacMillan 2004). We expect that it is not necessarily the high level of "project uncertainty" per se that leads to the recommendation to "flee" but the high level of evaluative uncertainty relative to a team's information processing capabilities that lead to this conclusion. A deeper understanding of the sources of uncertainty, and their implications for the value of flexibility, may impact the use of real options as a managerial tool. And indeed, as we have noted elsewhere, our model of real real options is as easy to employ in practice as is the conventional real options model.

In sum, this paper identifies and demonstrates the importance of introducing informational and behavioral realities into applications of real option theory. The analysis in the paper emphasizes how evaluative uncertainty and decision-maker rationality affect the value of flexibility that is the subject of the real options approach. By considering the influence of a more realistic setting, this paper offers an explanation of why managerial attempts to leverage the value of flexibility employing a real options approach tend to achieve results that are substantially inferior to those suggested by the traditional theory of real options. Perhaps even more importantly, the paper offers several opportunities for future research and presents an approach that can be exploited to examine these opportunities.

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Table 1: Summary of results

| | **Project Uncertainty** | **Evaluative Uncertainty** | **Limited Rationality** |
|---|---|---|---|
| Black-Scholes baseline | yes | no | no |
| Figure 2 (result)<br>Figure 3 (mechanism) | yes | yes | no |
| Figure 4 (result)<br>Figure 5 (mechanism) | yes | no | yes |
| Figure 6 (result)<br>Figure 7 (mechanism)<br>Figure 8 (mechanism) | yes | yes | yes |

Table 2: Parameter settings

| **Parameter and Value** | **Equation #** **Theory Sect.** | **Meaning** |
|---|---|---|
| $I_0 = 0$ | 1 | Investment at time 0 |
| $F_1 = 1$ | 1 | Cash flow at time 1 |
| σ | 3, 4, 6, 8 | Project uncertainty |
| $r_{dcf} = 0.3\ \sigma$ | 1 | Discount rate of future cash flows.[8] |
| $N_0 = 1/(1+0.3\sigma)$ | 1 | As defined by $I_0 = 0$, $F_1 = 1$, and $r_{dcf} = 0.3\sigma$ |
| $S_0 = 1$ | 4,6 | Initial price of asset that underlies option |
| $K = 1.28$ | 2 | Strike price of option |
| $r_{rf} = 0$ | 2, 4 | Discount rate used to adjust realized option value at time 1 to time 0 dollars. Also, interest rate used in Black-Scholes calculation. |
| $\alpha = \alpha^*$ | 9 | Firms update beliefs optimally |
| $\lambda = 0, 0.5, 1$ | 8 | Evaluative uncertainty defined as a share of project uncertainty |

[8] Implicitly, the more conventional firm level project discount rate (e.g., one that reflects the firm's cost of capital) may be considered to be embedded in this expression -- that is, at some level σ, $r_{dcf}$ is simply this firm level discount rate.

Figure 1: Stock call option payoff diagram

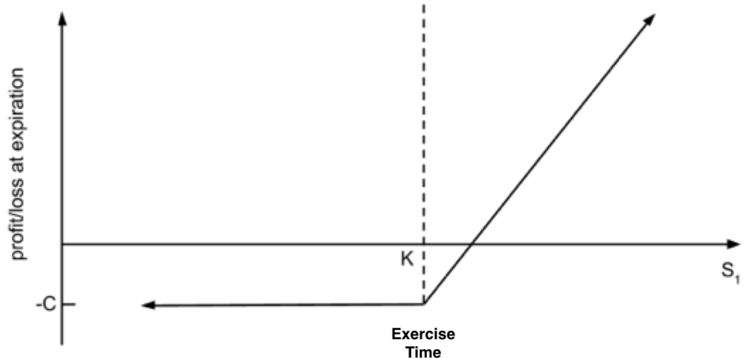

Figure 2: Option value with evaluative uncertainty (λ > 0) and adaptive rationality (α = α*)

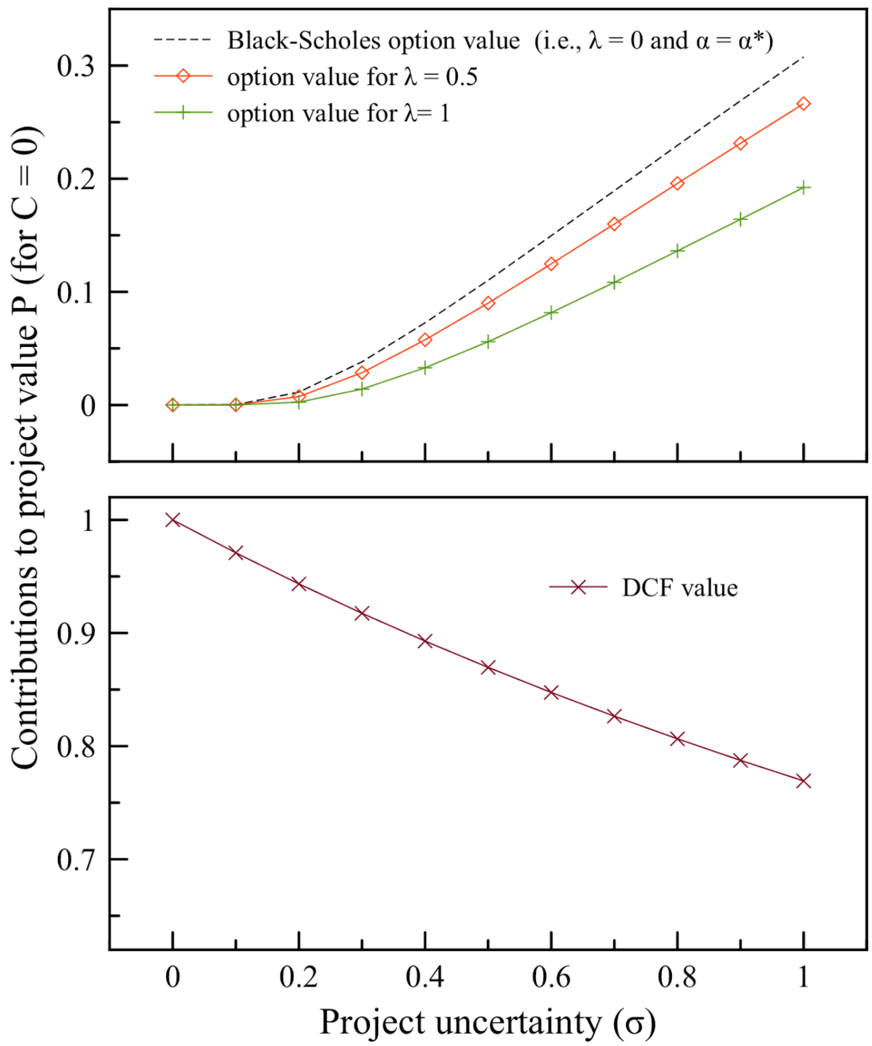

Figure 3: Evaluative regret decomposed into under- and over-investment errors ( λ = 0.5, α = α*)

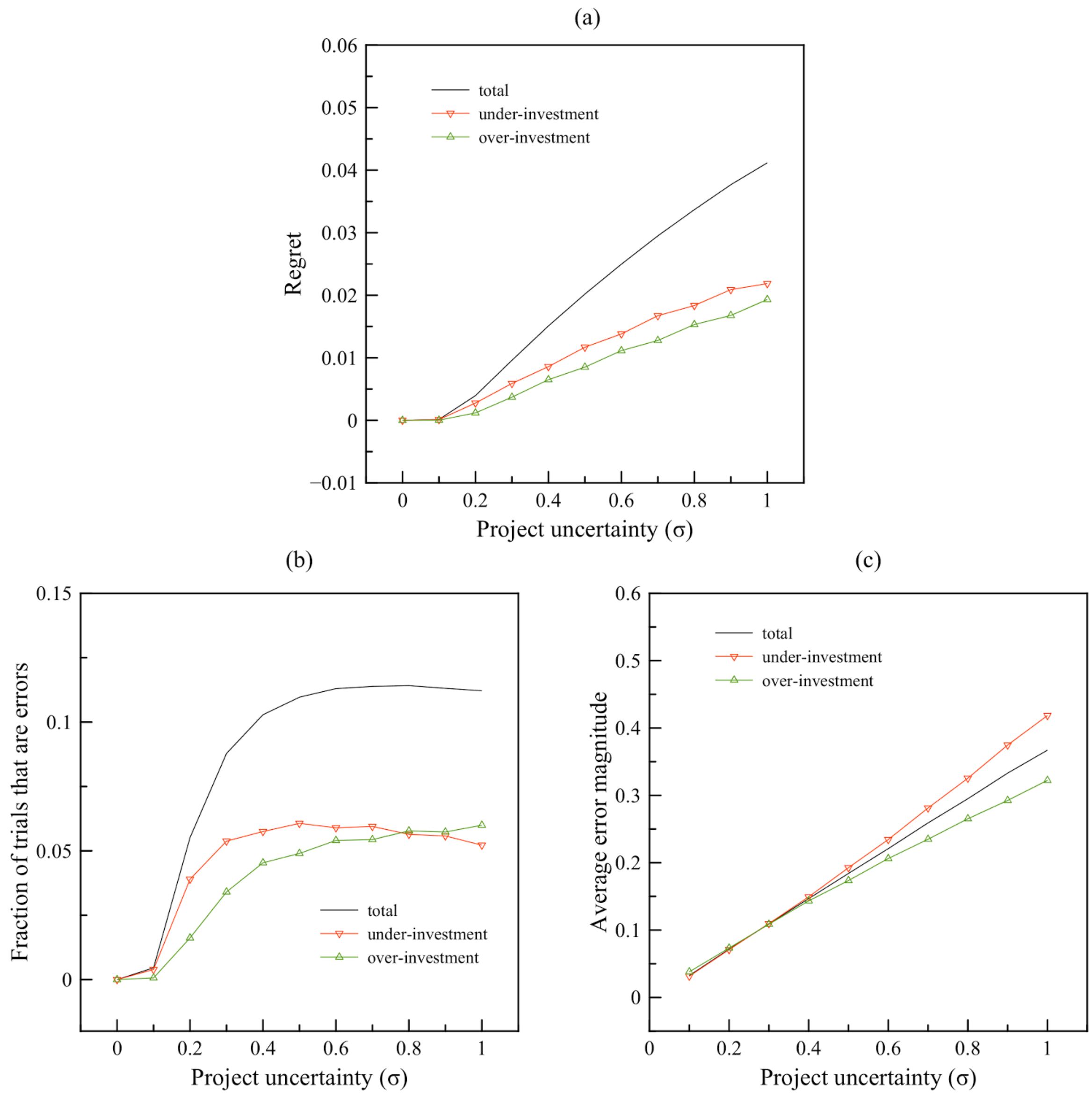

Figure 4: Option value with limited rationality ( $\alpha < \alpha^*$ ) and $\lambda = 0$

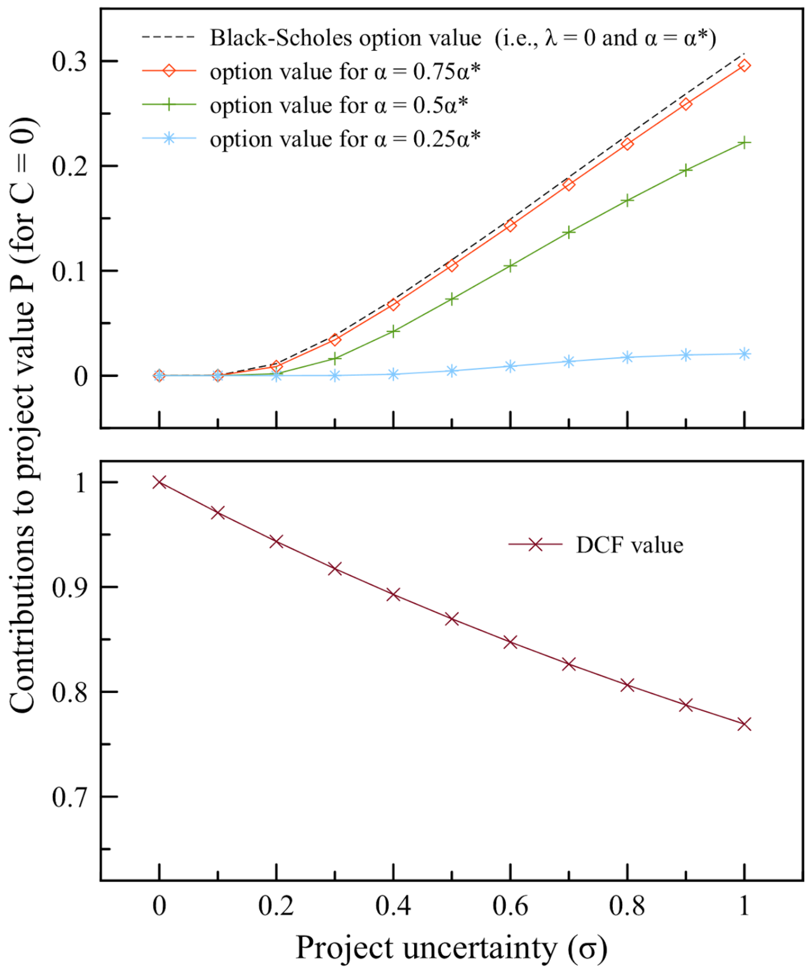

Figure 5: Behavioral regret decomposed into under- and over-investment errors ($\alpha = 0.75\alpha^*$, $\lambda = 0$)

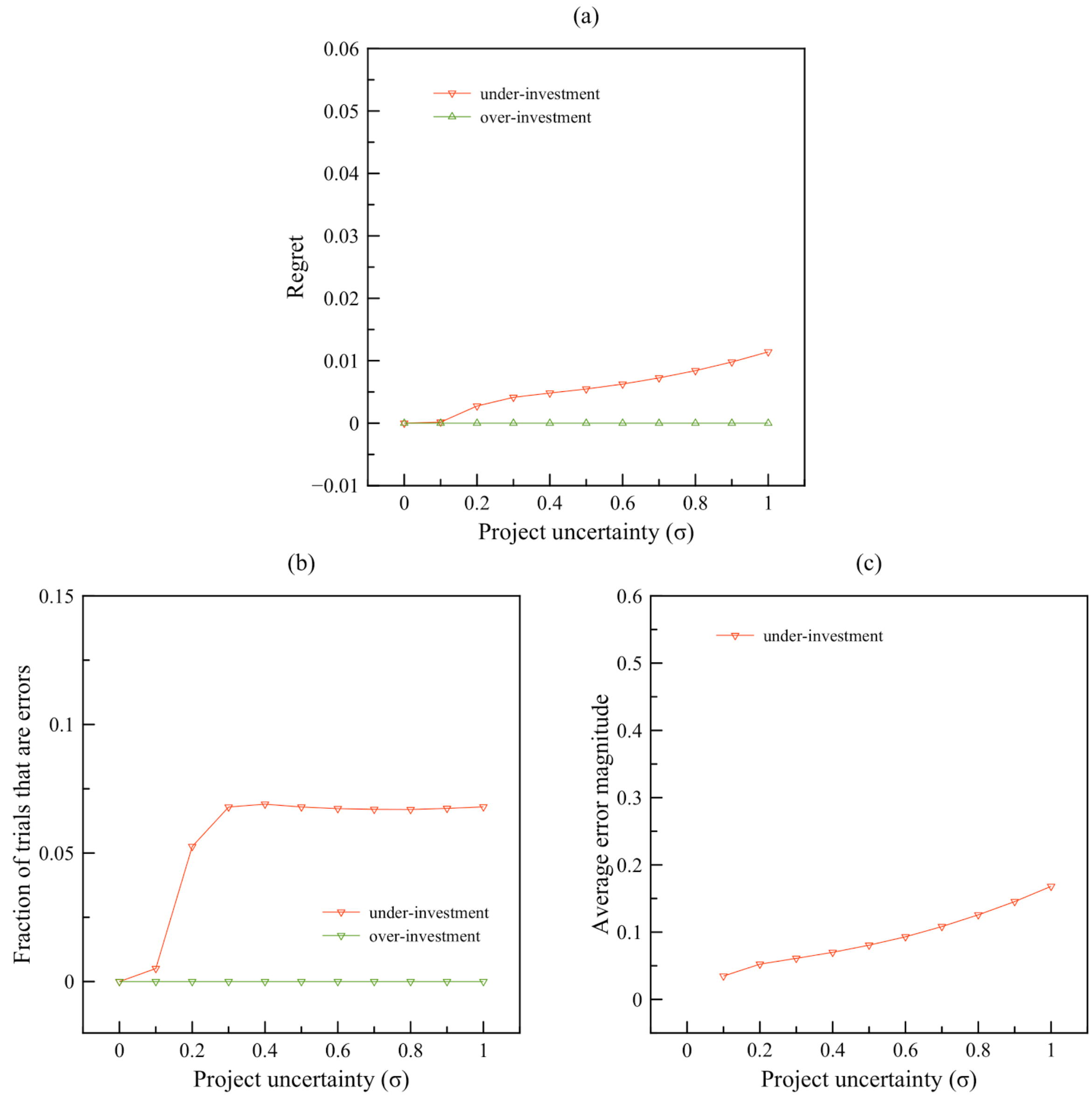

Figure 6: Option value with evaluative uncertainty (λ = 0.5) and limited rationality

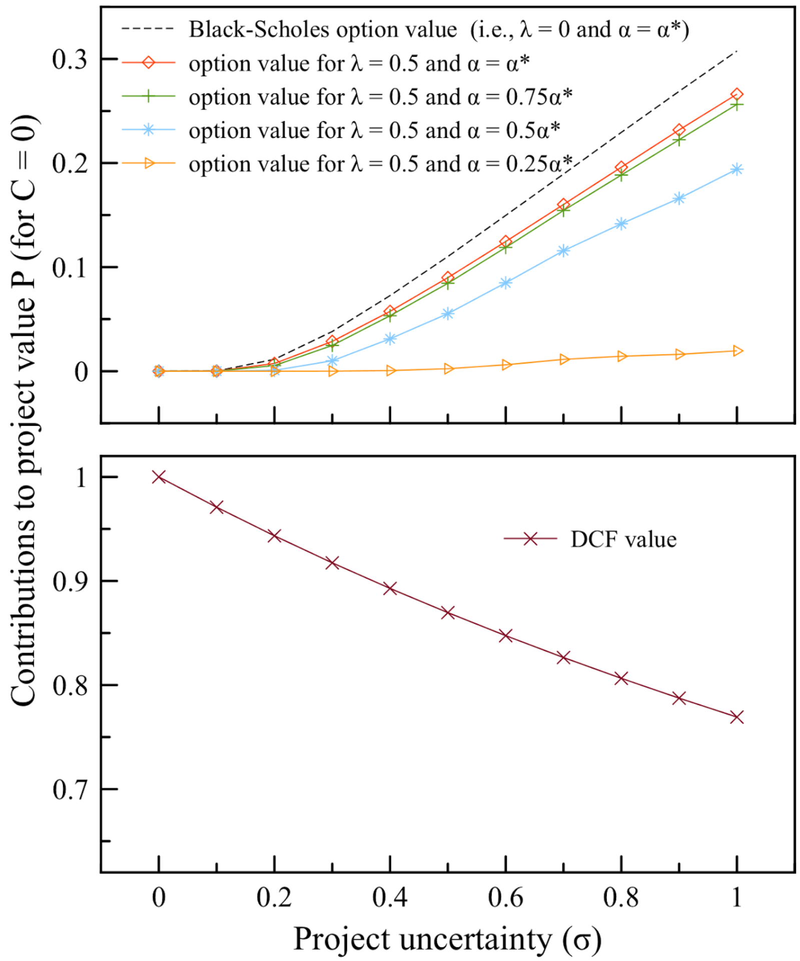

Figure 7: Regret decomposed into behavioral and evaluative errors (λ = 0.5, α = 0.75α*)

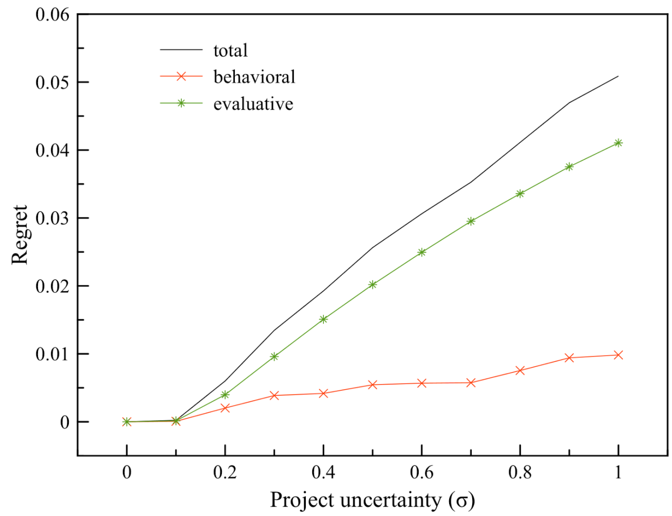

Figure 8: Regret decomposed into under- and over-investment errors (λ = 0.5, α = 0.75α*)