AN ATTENTION-AUGMENTED REAL OPTIONS APPROACH TO PUBLIC R&D INVESTMENTS

STEPHANIE FRANCIS GRIMBERT
(Corresponding author: s.grimbert@deusto.es)
Department of Economics and Finance
University of Deusto
&
CIRCLE
Lund University

JON MIKEL ZABALA-ITURRIAGAGOITIA
Department of Economics and Finance
University of Deusto
&
CIRCLE
Lund University
&
Department of Business, Strategy and Political Sciences
South Eastern University Norway

NICHOLAS VONORTAS
Department of Economics & IISTP
George Washington University
&
Department of Science and Technology Policy
University of Campinas

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ABSTRACT: Real options theory has gained momentum in the field of strategic management, both as a means for strategic reasoning and as a formal modelling method simulating real option valuation. In terms of real options, R&D investments offer a valuable learning space enhancing the upward potential and limiting downward risk of a firm's innovative activities, provided that attentional constraints are taken into account. Specifically, public R&D investments exert particular attentional constraints on public managers, as they involve externally distributed intelligence for tailored investments endowed with strong asset specificity aimed at increasing public value. To grasp the learning space provided by public R&D investments, we adopt an attention-augmented perspective to real options, which considers the bi-directional linkages between real options and the heterogeneity of public agencies, defined as the openness of their attention structures. We first reflect on how the learning space for real options can emerge from the heterogeneity of public agencies. We then reverse the relationship by considering that the strategic management of real options, when successfully taking into consideration behavioral biases, increases feedback learning processes, which enhance the heterogeneity of public agencies. Our framework is illustrated in the context of the Small Business Innovation Research program in the United States and its equivalent in Europe, the Pre-Commercial Procurement scheme.

KEYWORDS: real options, public sector heterogeneity, attention-based view, behavioral bias, Pre-Commercial Procurement, Small Business Innovation Research

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INTRODUCTION

A real option is "the right, but not the obligation, to take an action in the future" (Amram and Kulatilaka, 1999, p.5). In other words, option creation may or may not lead to the exercise of that real option regarding, for example, innovation projects (Klingebiel and Rammer, 2021; Ross, *et al*., 2018), corporate venturing (Ceccagnoli *et al*., 2018; Tong and Li, 2011), or new business development (Klingebiel, 2012; McGrath, 1999). By providing the opportunity to adapt flexibly to new information, real options enhance the economic value of an investment by limiting the downside losses expected initially (Kogut and Kulatilaka, 1994; Trigeorgis, 1997). The real options approach has gained momentum in the field of strategic management (Li *et al*., 2007; Trigeorgis and Reuer, 2017), on the one hand as strategic reasoning exempt of analytical modelling (real options reasoning) and on the other as a formal modelling method simulating real option valuation (real options valuation). Real options theory contributes to informing heterogeneity between organizations by "identifying critical bi-directional linkages" (Trigeorgis and Reuer, 2017, p.52) in such a manner that real options both emerge from and enhance heterogeneity when successfully recognized and managed (McGrath *et al.*, 2004; Tong and Reuer, 2007). The management of real options therefore causes variance in the value extracted from them (Bowman and Hurry, 1993; Kogut and Kulatilaka, 1994; McGrath, 1999; Tong and Reuer, 2006; Trigeorgis and Reuer, 2017), which places a high demand on managerial capabilities for execution.

Derived from the valuation of financial options (Black and Scholes, 1973; Myers, 1977), the conventional view on the value of real options considers that it is an increasing function of the uncertainty about the future value of the underlying asset by providing managerial flexibility as opposed to committing to an investment in the face of high uncertainty. However, bearing in mind that "one key challenge for the formal modeling of real options, compared to basic financial options, is that multiple sources of uncertainty

can affect the value of many real options" (Trigeorgis and Reuer, 2017, p.45), recent developments in real options theory have attempted to model the impact of different types of uncertainty on the value of real options. For example, Posen and colleagues consider "prospective" (i.e., future) and "contemporaneous" (i.e., current) categories of uncertainty, the latter being introduced to "relax the assumption that firms have objective information about the asset value that is both accurate and precise at any point in time" (Posen *et al*., 2018, p.1118). As a result of the value of real options being subject to both prospective and contemporaneous uncertainty, real options theory embraces a behavioral turn. As advocated by Trigeorgis and Reuer (2017), the inclusion of behavioral perspectives to real options theory enables exploring the effects of bounded rationality to the reliance on real options, according to which the value of real options would tend to be overestimated (Posen *et al*., 2018; Smit and Kil, 2017) because of potential execution errors.

The potential of real options theory has been explored in the literature on R&D investments (McGrath and Nerkar, 2004; Perlitz *et al*., 1999; Reuer and Tong, 2007). Considering R&D investments in real option terms provides an analytical grid for perceiving the increased financial value of a firm's innovative activities. Using this real option lens, new venturing projects are seen as small investments delimiting a learning space aimed at gradually improving the firm's knowledge about the future potential of a large panel of different technologies (Ross *et al*., 2018; Trigeorgis and Reuer, 2017; Vanhaverbeke *et al*., 2008). But given that "a wealth of information creates a poverty of attention" (Simon, 1971, p.40), approaching R&D investments in real options terms also allows for recognizing the attentional constraints that affect the realization of the potential value of real options (Barnett, 2005) by imposing the allocation of attention across multiple projects (Kim *et al*., 2016; March, 2001). Behavioral real options theory usefully complements an attention-augmented perspective to the valuation of real options in the

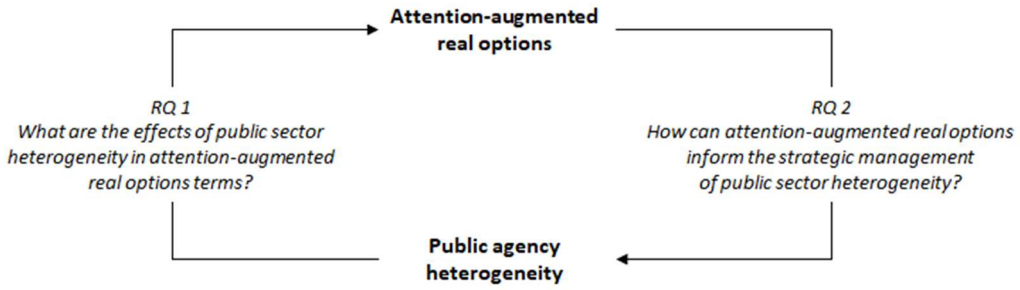
context of R&D investments. The volatility associated with R&D projects is determined by market uncertainty and technical uncertainty, which induce complexity for the accurate transfer of financial option pricing techniques to actual investment decisions (Smit and Trigeorgis, 2017; Vonortas and Desai, 2007). Hence, "there is an option value of additional information" (Huchzermeier and Loch, 2001, p.99) about project progress and market characteristics which explains "the gap between the financial payoff variability […] and operational uncertainty" (Ibid., p.86) and requires leaving space for improvement as a complementary type of real option under operational uncertainty.

Staged public R&D investments as is the case in the Small Business Innovation Research program in the US and its equivalent in Europe, the Pre-Commercial Procurement scheme, have also benefited from real options valuation techniques. They are considered more appropriate to fully capture the strategic value of investment opportunities than traditional capital budgeting techniques, which tend to penalize long-term investments (Vonortas and Desai, 2007; Vonortas and Hertzfeld, 1998; Vonortas and Lackey, 2003) endowed with "a high-risk/high-rewards approach to meet the technology vision" (Bonvillian, 2014, p.7). However, the literature on the strategic management of R&D investments through an attention-augmented real options approach has yet to be adapted to the specific context of public agencies, despite the particular attentional constraints exerted by relying on externally distributed intelligence. Public R&D investments assist the private sector in accelerating the introduction and commercialization of innovations endowed with strong asset-specificity (Casady *et al.*, 2023) but are aimed at increasing service performance and public value, where the utility function is unspecified. We address this gap by applying an attention-augmented real options approach to public R&D investments, which we define as *the right but not the obligation to acquire an asset given attentional constraints when there is both prospective and contemporaneous*

uncertainty. Our framework sheds light on the bi-directional linkages between an attention-augmented real options approach and the heterogeneity of public agencies as illustrated in Figure 1 below. Our first research question examines the effects of public sector heterogeneity in terms of an attention-augmented real options approach. Our second research question looks at how an attention-augmented real options approach can inform the strategic management of public sector heterogeneity.

Insert Figure 1 about here

Figure 1: Conceptual approach



Source: own elaboration based on Trigeorgis and Reuer (2017).

The remainder of this article is structured as follows. In the next section, we review prior literature on public R&D investments considered as real options, and on the link between heterogeneity and an attention approach to real options, before highlighting the behavioral turn of real options theory. We then conceptualize an attention-augmented real options approach to public R&D investments by exploring the bi-directional linkages by which real options both emerge from and enhance the heterogeneity of public agencies when managed strategically. We illustrate our framework in the context of the Small Business Innovation Research program in the US and its equivalent in Europe, the Pre-Commercial Procurement scheme, to identify the managerial implications of considering public R&D investments from an attention-augmented real options approach.

THEORETICAL BACKGROUND

Public R&D investments as real options

Following seminal contributions formulating R&D investments as an option (Lee 1982a, 1982b), the value of the opportunity (i.e., option) opened up by an early-stage R&D investment, potentially leading to a new technological area, "has been repeatedly used as a qualitative argument by research administrators in both the private and public sectors to support strategic, long-term research" (Vonortas and Hertzfeld, 1998, p.622). As a cornerstone between capital budgeting and strategic planning, real options thinking addresses the shortcomings of traditional valuation techniques in the context of the public sector, which tend to unduly penalize investments with long-term expected payoffs (Vonortas and Desai, 2007; Vonortas and Lackey, 2003), by disregarding the particularities of staged programs offering the possibility to discontinue funding after a given phase. Each stage of the research process "contributes something to the next not only in terms of enabling it by providing the necessary technical knowledge, but also in terms of decreasing the uncertainty involved in it by defining the question to be answered more accurately and by adding to the information concerning the operating environment" (Vonortas and Hertzfeld, 1998, p.628). Given the evolving uncertainty over the whole lifecycle of an R&D project, real options analysis enables accommodating changing risk profiles (Belz and Giga, 2018; Dixit and Pindyk, 1994) in the shape of differing discount factors, which reflect decreasing risk in various stages of technological development (Vonortas and Desai, 2007; Vonortas and Hertzfeld, 1998; Vonortas and Lackey, 2003).

In order for public R&D investments portfolio valuations to be discussed in terms of their potential value rather than as an investment budget (Belz and Giga, 2018), Vonortas and Desai (2007) examine how public R&D investments can be analyzed as chains of real options that capture the inherent flexibility of the management of strategic policy decisions. Due to the intrinsic characteristics of innovation---i.e., uncertainty of

the outcome, relevance of the timing of the investment, and irreversibility of committed resources)---Vonortas and Desai maintain that adopting a real options perspective allows addressing "the alleged chronic deficit between the calculated value of strategic, long-term projects and their true value" (2007, p.700) reflecting intangible strategic benefits (Trigeorgis and Reuer, 2017; Vonortas and Lackey, 2003). Thus, viewing R&D investments as real options opens up for actively managing and eventually altering a specific project portfolio once a certain policy trajectory has been undertaken. While using discounted cash flows for evaluating R&D investments posit that assets are held passively, options to modify projects provide valuable strategic flexibility to managers who "do not simply sit back and watch the future unfold" (Brealey and Myers, 2003, p.268).

Accounting for heterogeneity: An attention approach to real options

Based on Simon's (1955) influential work on bounded rationality, the Attention-Based View of the firm (Joseph *et al.*, 2024; Ocasio, 1997) offers a theoretical framework for extracting value from real options (Barnett, 2008). Variance in the value extracted from real options can be explained by how managers recognize and manage them (Bowman and Hurry, 1993; Kogut and Kulatilaka, 1994; McGrath, 1999; Tong and Reuer, 2006, 2007; Trigeorgis and Reuer, 2017), placing high demand on managerial "attention" skills (Simon, 1947, 1971). They rely on the organization's resources to identify potential courses of action considered as shadow options awaiting recognition (Andriani and Cattani, 2024; Bowman and Hurry, 1993). An Attention-Based View complements real options reasoning by incorporating managerial decision-making under uncertainty, thereby determining if the portfolio of options will ultimately lead to value creation or value destruction for the firm (Barnett, 2008; Bauer and Friesl, 2024). It encompasses the decision-making process at the operational and governance levels by enlightening the respective foci of attention of project champions and of upper

management as regards the portfolio of options across various projects, according to a firm's particular structural conditions (Barnett, 2008; Maritan, 2001; Ocasio and Joseph, 2005). Those structural conditions, which "explain how firms distribute and regulate the attention of their decision-makers" (Ocasio, 1997, p.188), comprise concrete procedural and communication channels (operated by the firm at the operational and governance levels) and contextual attention structures (present in the general social, cultural, and economic climate of the organization) (Barnett, 2008; Kaufmann *et al.,* 2021), influencing the ability of managers to notice, create, and exploit opportunities.

Such "an attention-augmented real options framework can be a valuable strategic tool" (Barnett, 2005, p.70), as long as attentional constraints are considered for effectively applying options method. Public R&D investments entail specific transaction risks by aiming at creating "a valuable option to a technology that either it or the private sector can exercise at some predetermined future date" (Vonortas and Hertzfeld, 1998, p.628). Such investments "are often regarded as having high asset specificity"[1] (Casady *et al.*, 2023, p.4), whilst aiming at increasing service performance and public value, the utility of which is unspecific as it is a bundle of accountability systems and collective preferences (Hefetz and Warner, 2004; Hirsch and Osborne, 2000). Attentional constraints are thus particularly strategic in the case of the public sector, for which R&D investments engage externally distributed intelligence to develop solutions outside its organizational boundaries for addressing core wicked societal problems (Crowley and Head, 2017; Rittel and Weber, 1973) and create public value (Crosby *et al.*, 2017; Moore, 1995).

Real options theory has previously embraced the notion of firm heterogeneity viewed as knowledge, competencies, and learning that are at the base of capabilities

[1] Asset specificity refers to the degree to which an asset that is used to support a transaction can be redeployed to alternative uses and users without loss of productive value (Williamson, 1985, 1996).

allowing firms to exploit new opportunities differently despite a common uncertain environment (Tong and Reuer, 2006, 2007; Trigeorgis and Reuer, 2017). For instance, Vanhaverbeke and colleagues (2008) adopt a real options perspective for the evaluation of sequential corporate investment decisions to outline the benefits of external corporate venturing as learning spaces for innovative activities. In turn, learning affects the firm's observation and interpretation of exogenous signals leading to the option's exercise or abandonment (McGrath *et al.*, 2004; Tong and Reuer, 2007). In line with an attention-augmented real options framework, which considers firms as "options to learn, rather than as a bundle of resources and capabilities" (Trigeorgis and Reuer, 2017, p.58), heterogeneity in organizations can be defined as the breadth of their "cognitive frames and knowledge platforms" (Ibid.).

The behavioral turn in real options theory

In an attempt to adapt real options to real-world contexts, the research literature on real options also endeavors to embrace its limitations stemming from bounded rationality, information imperfection, and behavioral biases such as the path-dependent nature of strategic decisions (Leiblein *et al.*, 2017; Posen *et al.*, 2018; Tiwana *et al.,* 2007). As one of the main approaches to conducting real options research (Trigeorgis, 2014; Trigeorgis and Reuer, 2017), this behavioral turn suggests that a biased perception of uncertainty leads to distorted valuations analyses of real options, subject to executive optimism (Miller and Shapiro, 2004; Smit and Kil, 2017). Trigeorgis specifically accounts for bounded rationality in behavioral real options valuation that accommodates different assumptions and features about environmental, organizational, and human realities, and shows the impact of information imprecision, behavioral characteristics, biases, and "associated indirect effects related to ambiguity cautiousness or risk-taking attitudes driven by bounded rationality" (2014, p.27).

One of the main factors affecting the valuation of real options and limiting the analogy between financial options and real options concerns the volatility parameter, in other words, the "potential variation of the value of the underlying asset between the initiation and the expiration of the option" (Vonortas and Desai, 2007, p.705). In the case of real options, volatility is a function of different types of uncertainty (Dixit and Pindyck, 1994; Pindyck, 1993). Originally identified as "technical uncertainty," an endogenous type of uncertainty resolved by investment and "input cost uncertainty," an exogenous uncertainty necessitating information acquisition (Pindyck, 1993), real options portfolio management is subject to such diversifiable and non-diversifiable risks (Huchzermeier and Loch, 2001;Vonortas and Desai, 2007) with contradictory effects on the value of the real option (Perlitz *et al.*, 1999). Situated at the junction between the two previous forms of uncertainty, McGrath identifies a third type of uncertainty as external to the firm but possibly influenced by strategic action such as "amplifying pre-investments," aimed at a firm-specific "idiosyncratic reduction of uncertainty" (1997, p.978), which unambiguously increases the value of the real option. This strategic uncertainty reduction is not trivial in the context of the public sector, as discussed later.

Integrating the behavioral turn of real options theory and the underpinning effects on the definition of uncertainty, Leiblein and colleagues introduce behavioral biases in sequential decision-making under uncertainty, by distinguishing "prospective uncertainty" and "contemporaneous uncertainty" (2017, p.2590). Prospective uncertainty is derived from the real options literature and comprises the types of uncertainty described earlier (i.e., technical and market uncertainties). Contemporaneous uncertainty pertains to feedback learning theory, whereby a firm receives information regarding the current value of an asset in the shape of noisy feedback that is neither accurate nor precise at any point in time and updates its beliefs (themselves noisy) based on this feedback. At the time of

the option exercise decision, two behavioral biases "impact the efficacy of feedback learning" (Posen *et al.*, 2018 p.1114): precision bias (reflecting the level of confidence in one's prior beliefs) and confirmation bias (based on individual perceptions of confirming and disconfirming evidence). A behavioral theory of real options. therefore, takes into consideration boundedly rational decision-makers whose behavioral biases can lead to real options execution/termination errors increasing downside risk and reducing potential upside benefit.

EFFECTS OF PUBLIC SECTOR HETEROGENEITY IN ATTENTION-AUGMENTED REAL OPTIONS TERMS

*The case of small business innovation research /p*re-*commercial procurement*

The advantages of heterogeneity can be understood in real options terms as increasing the learning space for innovating organizations through small learning investments (Trigeorgis & Reuer, 2017; Vanhaverbeke *et al.*, 2008). However, attentional constraints need to be considered for the potential value of a real option to materialize in realized value, for "inattentive managers will be unaware of important events in the real option process, overlook shadow options within the firm and its environment, and miss time-sensitive strike signals" (Barnett, 2005, p.68). In the context of the public sector, such attentional constraints are particularly strategic since R&D investments involve high transaction risks due to both their strong asset specificity, and their highly unspecific objective of increasing public value by relying on external knowledge sources. To grasp the learning space provided by public sector heterogeneity, we adopt an attention-augmented perspective to real options, which enables us to explore the effects of attentional constraints on the selection and management of project portfolios.

In their behavioral approach to real options, Leiblein and colleagues define real options as "the right but not the obligation to acquire an asset when there is both prospective and contemporaneous uncertainty" (2017, p.2598), thereby focusing on the

behavioral biases affecting portfolio management. We graft this definition of real options within an attention-augmented real options approach, encompassing the attentional constraints faced by public managers for both portfolio selection and management. Based on Barnett's (2008) model of real option portfolio selection and management, we depict how attentional constraints exercised by the concrete and contextual attention structures explain which real options any given manager will attend to and act on and which they will not determine the value created by the real options. This perspective leads us to define attention-augmented real options as the right but not the obligation to acquire an asset given attentional constraints when there is both prospective and contemporaneous uncertainty.

We then examine, through this attention-augmented real options approach, the learning space funnel – as delimited by the concrete and contextual attention structures – provided by public sector heterogeneity. In particular, we introduce how the concrete procedural and communication channels and the contextual attention structures inherent to the public agency determine which options are noticed; which options are championed by middle management and received positively by senior management; and which options are ultimately held within a portfolio. We illustrate our framework in the context of the Small Business Innovation Research (SBIR) program in the US, which has its equivalent in Europe in the so-called Pre-Commercial Procurement, (PCP) as two examples of staged public R&D investments (Belz and Giga, 2018; Selviaridis, 2021), which include a selection phase and a management phase (as depicted in Table 1). To date, research regarding SBIR and PCP has mostly focused on their benefits, with scarce consideration given to the programs' "investments as a research portfolio managed under uncertainty" (Belz and Giga, 2018, p.76).

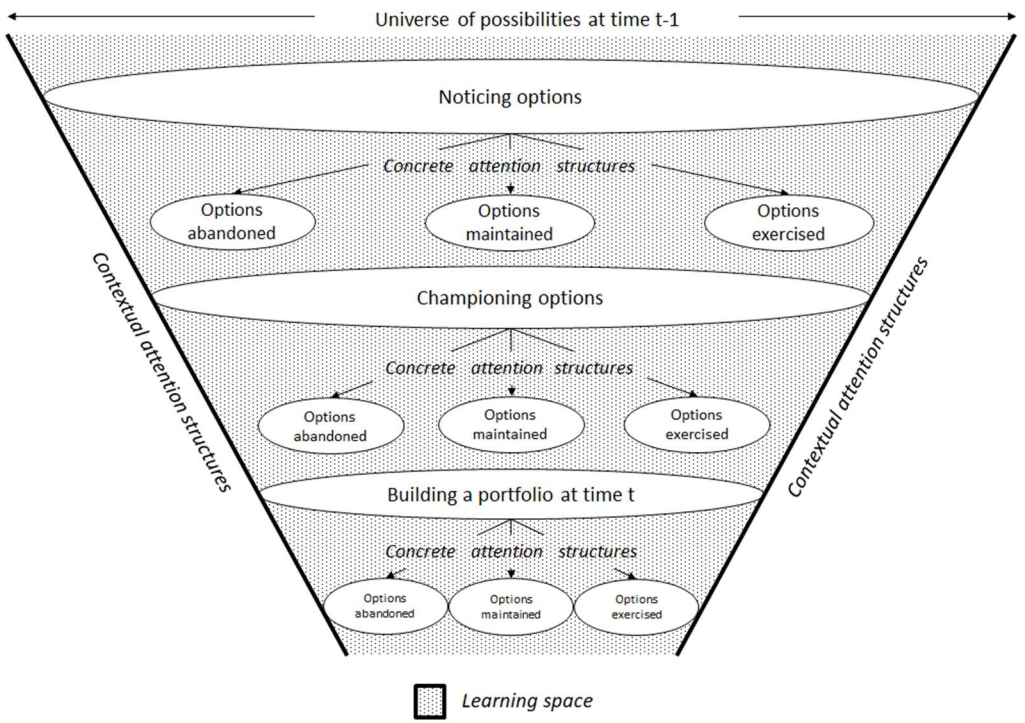
The SBIR program is one of the most important public policy programs in the US (Audretsch, 2003; Wessner, 2001) for addressing underinvestment in R&D and promoting diversity in the population of firms doing R&D (Audretsch *et al.*, 2019; Scott, 2000). The SBIR program aims to promote the role of the government as an entrepreneur (Link and Link, 2009; Link and Scott, 2010), leading to the generation of high-tech firms and the commercialization of their innovations (Lerner, 2000; Qian and Haynes, 2014), thereby contributing to competitiveness and growth. The SBIR program was created in 1982 through the Small Business Innovation Development Act (Small Business Innovation Development Act, 1982) and was structured in three phases (proof-of concept, consolidation, and commercialization), with the SBIR program funding the first two (Gallo, 2021; Link *et al.*, 2022). The SBIR program is an antecedent of the PCP scheme adopted by the European Union in 2006 (Edquist and Zabala-Iturriagagoitia, 2015). PCP is meant to provide the missing link in the development of completely new "yet-to-be-designed" technology research in Europe (European Commission, 2006a, p.18). It is defined as "a process by which public authorities in Europe can steer the development of new technologically innovative solutions that can address their specific needs" (European Commission, 2006b, p.2). The PCP cycle (as outlined by the European Commission, 2008) also comprises three phases (solution exploration, prototyping, and testing).

At each stage of the SBIR/PCP cycles, projects can either be abandoned, maintained, or exercised in the form of procurement. These projects can thus be considered as sequential investments since "the investment is made in a phased manner, with the commencement of a subsequent phase being dependent on the successful completion of the preceding phase" (Vonortas and Desai, 2007, p.702). Upon completion of the selection phase, both the SBIR and the PCP cycles end with field tests for the projects retained within the portfolio, which may – or may not – lead to a consecutive

regular procurement tendering on behalf of the public agency funding the scheme (Edquist and Zabala-Iturriagagoitia, 2015). Hence, they provide an ideal setting for illustrating the framework presented in this article, as instruments giving the public sector the right, but not the obligation to acquire socially valuable emerging technologies (Audretsch *et al.*, 2019) developed externally.

Insert Table 1 about here

Table 1: The learning space funnel for portfolio selection and management

		SBIR		PCP
Portfolio selection	*The types and number of seeds planted*	**Phase 1**: analogous to proof-of-concept research targeting agency or societal needs, generally ranging between USD 50,000 and USD 250,000 (~6 months). **Phase 2**: aimed at consolidating the scientific, technical, and commercial potential of the awarded projects. Usually capped at USD 750,000 (~2 years).		**Phase 1**: a pre-commercial tendering is initiated by a public agency and leads to feasibility studies being received from candidate companies (~6 months). **Phase 2**: some of the candidate companies are shortlisted until a first, non-commercial prototype is obtained (~2 years).
Portfolio management	*The attention given to burgeoning plants*	**Phase 3**: aimed to encourage the developed small firms to pursue third-party funding to finance the commercialization of their technologies.		**Phase 3**: once these prototypes are assessed, some of the candidate companies are invited to test a limited number of these prototypes under field conditions (~2 years).

Source: own elaboration based on Barnett (2008).

Proposed effects of heterogeneity on real options

For each stage of the funnel depicted in Table 1 (i.e., noticing options, championing options, and building a portfolio of options), we identify the effects of heterogeneity by informing how the learning space for real options can emerge from the heterogeneity of public agencies in terms of the openness of their (concrete and contextual) attention structures. In doing so, we explore in the context of the public sector the first of the bi-directional linkages emphasized by Trigeorgis and Reuer (2017) between a public agency's heterogeneity and real options. The reverse linkage, which illustrates how the strategic management of the learning space for real options can enhance the heterogeneity of public agencies, will be considered in the next section focused on the decisions to maintain, exercise, or abandon options.

Insert Table 2 about here

Table 2: Effects of heterogeneity on the learning space for real options

Stages of portfolio selection and management	**Concrete procedural and communication channels**	**Contextual structures**	**Effects on the learning space in attention-augmented real options terms**
Noticing options	Information infrastructure	Collaboration with external actors	- Comprehensive formulation of the tendering - Diffusion of the tendering for noticing shadow options
Maintaining noticed options, Exercising noticed options, Abandoning noticed options			
Championing options	Project review process	Autonomous strategic activity	- Diversity of projects championed - Level of championing
Maintaining championed options, Exercising championed options, Abandoning championed options			
Building a portfolio of options	Diversity of internal profiles involved	Political backing End-user focus	- Number of projects adopted - Novelty of projects adopted - Likelihood of future third party funding of prototypes
Maintaining created options, Exercising created options, Abandoning created options			

Source: own elaboration based on Barnett (2008).

Noticing options

The SBIR/PCP cycle initiates with the identification of needs, which may pertain either to the specific internal requirements of the agencies funding the SBIR/PCP or address societal needs more broadly. In the latter scenario, the public sector assumes the role of an intermediary and coordinator, facilitating the connection between societal needs and the potential responsiveness of corporate firms. During this initial stage of the learning space funnel, the establishment of robust information infrastructures becomes pivotal for timely identification of needs and assessment of whether private firms possess the required capacities for developing solutions in time. In both cases, public agencies may engage potential partners for collaborative innovation projects. Consequently, it is reasonable to anticipate that the more externally (internally) oriented a public agency's attention structures are, the more (less) likely the formulation of the challenge to be met will involve external actors. As a result, the broader the participation, the more comprehensive the definition of the tendering documents. Following the identification of needs and the definition of the required solution functions, the responsibility for the diffusion of the tender resides within the public sector, with the aim of maximizing outreach. It is thus anticipated that the more externally (internally) oriented a public agency's attention structures are, the more (less) likely its decision-makers will diffuse the tendering to reach shadow options in new markets.

Championing options

The next stage in the learning space funnel encompasses the project review process, overseen by middle management, where the noticed options are championed. There, the influence of heterogeneity on the learning space derives from the openness of this concrete attention structure. Adopting an open approach in the review process allows for the inclusion of multiple evaluation criteria in the assessment of project options.

Accordingly, the more externally (internally) oriented the project review process, the more (less) diverse the championed projects in the SBIR/PCP cycle will be. Championing options requires middle managers to exhibit autonomy in accompanying the bidding firms along the SBIR/PCP process, up to the stage in which their projects will be assessed by upper management. The strategic autonomy of middle management goes hand in hand with the degree of ownership they assume, as this will directly influence their commitment to pursue the goals posed by the SBIR/PCP. Hence, the stronger (weaker) the perceived support for autonomous strategic activity within a public agency, the greater (lesser) the ownership of projects by middle management will be and the larger (lower) the percentage of candidate projects championed at that public agency.

Building a portfolio of options

In the last stage of the learning space funnel, where prototypes are subject to testing for scaling-up, the greater (lesser) the political backing to upper managers in governance channels at a public agency, the higher (lower) the number of championed options bought by upper managers at that public agency will be. The novelty of the projects retained can be enhanced by the diversity of internal profiles involved in the review of the prototypes, ensuring that the solution functions receive a multi-dimensional assessment. It can therefore be anticipated that the more (less) widespread and diverse the profiles, competences and capabilities of top management in public agencies in charge of SBIR/PCP, the more (less) novel the options entering the test phase of the program will be. For the selected prototypes to comprehensively respond to the demands posed by the tender documents, the contextual attention structures of public agencies need to be oriented towards the end-users of the developed solutions, whether specific agencies and/or the broader society. Therefore, the larger (lower) the diversity of societal actors involved in the review and testing of the prototypes, the higher (smaller) the likelihood

of the supplying firm to pursue third-party funding to finance the commercialization of their prototypes.

STRATEGIC MANAGEMENT OF PUBLIC SECTOR HETEROGENEITY IN ATTENTION-AUGMENTED REAL OPTIONS TERMS

In this section, we aim to explore how an attention-augmented real options approach can inform the strategic management of heterogeneity in the public sector. To do so, we follow Trigeorgis and Reuer (2017) by considering the reverse linkage between real options and the heterogeneity of organizations, whereby real options, when pursued successfully taking into consideration behavioral biases, can enhance the heterogeneity of public agencies in terms of the openness of their (concrete and contextual) attention structures.

Uncertainties in real options

Adjoining contemporaneous uncertainty to prospective uncertainty posits that the management of a real option portfolio may be subject to execution errors due to behavioral biases (Leiblein *et al.*, 2017; Posen *et al.*, 2018). As depicted in Table 3 below, we adopt Posen and colleagues (2018) definition of behavioral biases as precision and confirmation biases to explore their effects in terms of risks of execution errors. We bundle under-precision and negative confirmation biases within the "over-execution" type of risk, meaning that the real option would be executed despite its value remaining high in the context of high prospective uncertainty. Conversely, we bundle over-precision and positive confirmation biases within the "under-execution" type of risk, leading real options to be either maintained or terminated despite the level of prospective uncertainty having decreased.

In the context of SBIR/PCP, prospective uncertainty equates to technical and market uncertainties. The SBIR/PCP process, understood as a technology push instrument in relation to innovation (Edquist and Zabala-Iturriagagoitia, 2015), is meant to provide

R&D-based solutions to existing challenges under the form of testable prototypes. Technical risk resides "in the technical characteristics of the service or product or in its production, and thus originates from the suppliers' side" (Edler *et al.*, 2015, p.93). Throughout the SBIR/PCP cycle, projects go through several sequential assessments that progressively resolve prospective uncertainty, but without necessarily meeting in a satisfactory manner the requirements of the tender. Correspondingly, for a given project, the value of the real option within a portfolio of SBIR/PCP projects decreases as prospective uncertainty declines. Assuming that there would be no contemporaneous uncertainty, a SBIR/PCP cycle resulting in the development of a successful prototype should thus lead to the exercise of the option when there is no more prospective uncertainty; in other words, to the procurement of the prototype once its technical suitability has been field tested. Public agencies are also confronted with heterogeneous market uncertainty, which impacts their rate of success in exercising options through procurement. For instance, the Department of Defense, and its satellite agencies, are the most successful - the reason being that the Department of Defense is the market. The Department of Energy has been moderately successful because it funds pilot programs in specific areas, but it does not define the energy market, being an already complex established legacy sector (Bonvillian, 2014, 2018). Hence, different agencies operating in different sectors unevenly use their "procurement power for initial product market creation" (Bonvillian, 2014 p.4).

While different agencies are faced with disparate levels of prospective uncertainty, the existence of contemporaneous uncertainty introduces a third category of risk. Behavioral biases in the various assessments conducted along the SBIR/PCP cycle represent an organizational type of risk "leading to failure or under delivering" (Edler *et al.*, 2015, p.93). In the "over-execution" type of risk, the real option would be executed

despite its value remaining high in the context of high prospective uncertainty. For example, a prototype would be procured despite its technical suitability to the public agency's need being subject to interpretation, and its commercialization prospects unclear. In the "under-execution" type of risk, the real option would be either maintained or terminated despite the level of prospective uncertainty having decreased. In this case, a funded SBIR/PCP project would either be maintained in spite of its questionable prospects, or else be unduly denied access to the next phase of the SBIR/PCP cycle despite the solution being potentially technically suitable.

Insert Table 3 about here

Table 3: Behavioral real options applied to SBIR/PCP

	Low prospective uncertainty *Low value of the real option due to resolved technical risk*	**High prospective uncertainty** *High value of the real option due to unresolved technical risk*
Contemporaneous uncertainty (i) *Organizational risk due to over adjustment to new/disconfirming information*	Option exercise adequate *Procurement of prototype*	Risk of over-execution
Contemporaneous uncertainty (ii) *Organizational risk due to under adjustment to new/disconfirming information*	Risk of under-execution	Option maintenance adequate *Next phase of the cycle*

Source: own elaboration based on Leiblein *et al.* (2017) and Posen *et al.* (2018).

Strategic management of uncertainties

Behavioral biases account for variance in the value extraction from a real option portfolio (Leiblein *et al.,* 2017; Trigeorgis and Reuer, 2017). Each decision regarding the management of R&D investments portfolios should therefore aim at incorporating feedback learning opportunities to lower the frequency of errors (Posen *et al.*, 2018). The strategic management of contemporaneous uncertainty holds the potential to increase the quality of the feedback learning processes of public agencies, which affects their heterogeneity defined by the openness of their (concrete and contextual) attention

structures. In Table 4 below, we illustrate the effects of feedback learning opportunities on the concrete and contextual attention structures of the public agency in terms of information processing and belief-updating abilities (Leiblein *et al.*, 2017).

Insert Table 4 about here

Table 4: Effects of the learning space for real options on heterogeneity

	Strategic management of the learning space in attention-augmented real options terms	**Effects on concrete procedural and communication channels**	**Effects on contextual structures**
	Feedback learning opportunities	***Information processing***	***Belief updating***
Maintaining options	- Amplifying pre-investments	Evaluation process	Salience of past failures
Exercising options	- Rate of procurement - Timing of procurement	Diversity of internal profiles involved	Collaboration with external actors Political backing
Abandoning options	- Denying additional resource allocations	Termination procedure	Assessment of risk

Source: own elaboration based on Barnett (2008) and Leiblein *et al.* (2017).

When deciding to maintain an option, public agencies can strategically invest in an "idiosyncratic reduction of uncertainty" (McGrath, 1997, p.978) with amplifying pre-investments. Regarding the effects on the attention structures in terms of information processing and belief updating capabilities, such investments require rethinking the evaluation process and the management of past failures. Both types of attention structures need to leave space for learning and experimentation, if R&D investments are to enable the public agency to scan a wider set of technologies. It can be expected that for more options to be maintained with amplifying pre-investments, the evaluation process will be more externally oriented, and the salience of past failures weaker.

At the time of the decision to exercise an option in the shape of the procurement of a prototype, the effectiveness of the SBIR/PCP cycle can be determined by the suitability of the promoted projects' results in addressing, in a timely manner, the public agency's or societal needs. Considering that public agencies face heterogeneous market conditions (Bonvillian, 2014, 2018), different success rates in terms of real options exercise through procurement does not imply anything about the quality of funded research or its option value. However, it indicates that managers in these public agencies have different behaviors regarding options exercise (in the form of the procurement of the prototype), and thus heterogeneous feedback learning processes. This heterogeneity suggests first that information processing about the maturity of the technology to be procured and of market conditions leads to engaging with a diversity of profiles internally, whether from upper- and middle-management, or from different departments within the public agency. Second, improving the success rates in terms of real options exercise will encourage the public agency to collaborate with external actors, as well as ensuring renewed political backing.

Abandoning options also requires a feedback learning process for denying additional resource allocations to the maintenance of options when the project has deviated from the needs expressed in the tender. As a result, the termination procedure and the assessment of risk by the public agency will allow for some flexibility for public managers to recognize failure, rather than unduly promoting projects in a systematic (and bureaucratic) manner through the complete SBIR/PCP cycle.

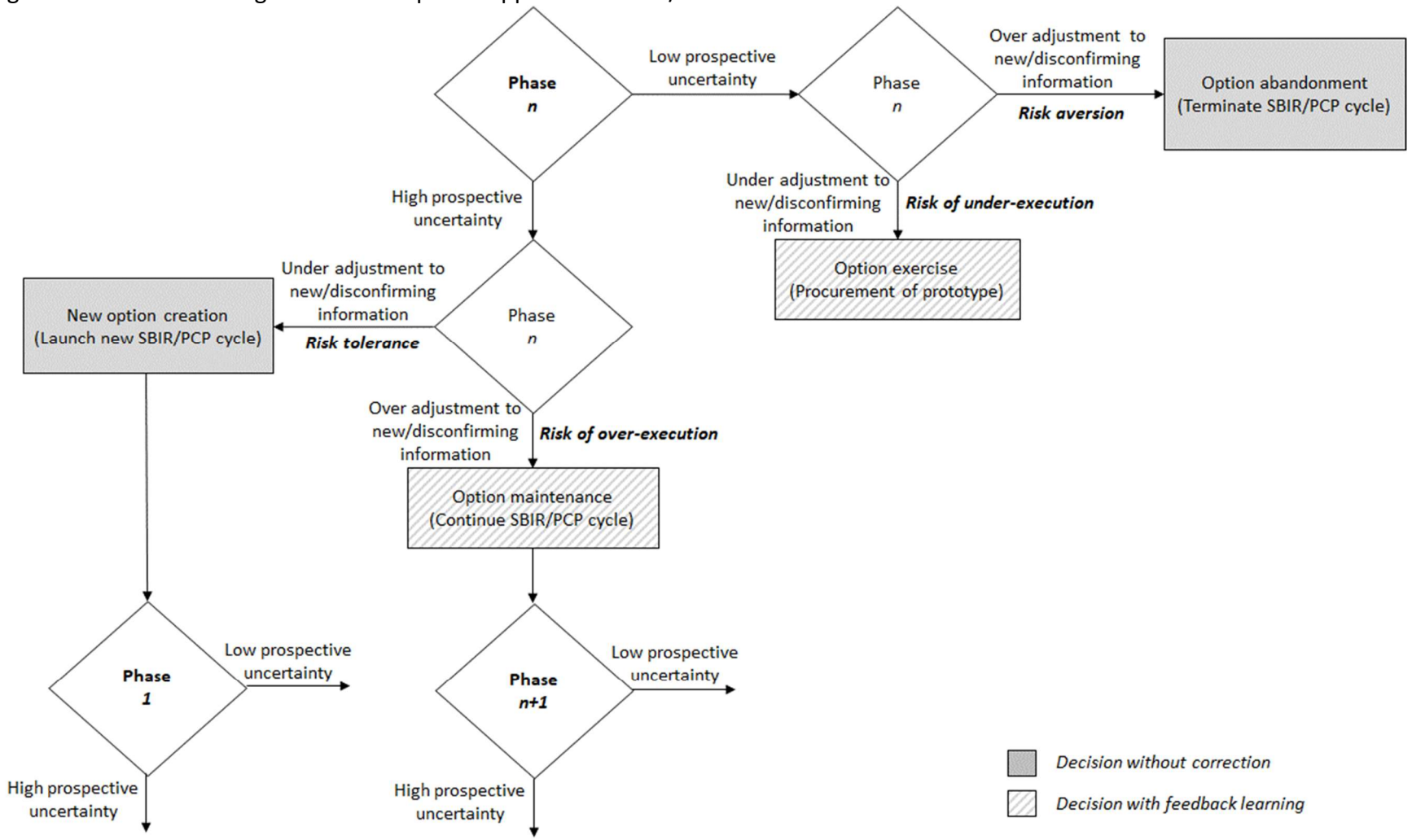
Uncertainties and risk management

Programs such as the SBIR or PCP find their roots in an entrepreneurial understanding of the innovative action of public agencies, whereby "the innovative use of public resources" (Link and Scott, 2010, p.590) is subject to entrepreneurial risk

stemming from uncertainty. In the context of the public sector, "stamina and sophisticated risk management are needed in order to cope with innovations" (Edler and Georghiou, 2007, p.960), and develop an organizational culture which allows risk-taking (Edler *et al.*, 2015; Link and Scott, 2010). Such risk management – of both the technical and market risks related to prospective uncertainty and the organizational risk linked with contemporaneous uncertainty – can benefit from our real options approach to public R&D investments as "an essential element in the pursuit of the public interest" (Bracci *et al.*, 2021, p.206).

Insert Figure 2 about here

Figure 2: An attention-augmented real options approach to SBIR/PCP



Source: own elaboration based on Barnett (2008) and Posen et al. (2018).

Public sector organizations are generally considered to be risk averse, which entails inefficiencies in the context of procurement (Edler *et al.*, 2015). We consider that traditional risk management, in an attempt to remedy the risk aversion of public agencies by encouraging them to take calculated and planned risks, only considers the management of prospective uncertainty. In Figure 2, we depict risk aversion and risk tolerance in the cases of low prospective uncertainty and high prospective uncertainty, respectively. Risk aversion can manifest itself in the form of option abandonment, in spite of a low prospective uncertainty, whilst risk tolerance appears in the form of new option creation, regardless of the high level of prospective uncertainty. In both cases, the decisions represent an over-reaction to the signals received by the public agency, and risk management will tend to pursue the objective of striking a balance between risk aversion and risk tolerance.

By considering contemporaneous uncertainty, our real options management of SBIR/PCP further considers that public agencies need to develop capabilities to effectively manage organizational risk, on top of technical and market risks (Grimbert *et al.*, 2024). The real options literature has long considered that a greater focus should be given to the relationship between real options and capabilities (Barnett, 2003; Kogut and Kulatilaka, 2001). Following Leiblein and colleagues' statement that "undertaking a real option may require substantial learning" (2017, p.2595) to process information and update beliefs in the most efficient way, Figure 2 illustrates feedback learning opportunities. In the case of low prospective uncertainty, a risk of under-execution stemming from an under-adjustment to new/disconfirming information needs to be alleviated for the public agency to exercise its option and conduct regular procurement. Conversely, in the case of high prospective uncertainty, a risk of over-execution coming from an over-adjustment to new/disconfirming information requires correction for the public agency to maintain its option and continue the SBIR/PCP cycle.

The latter circumstances illustrate how considering the behavioral biases inherent to contemporaneous uncertainty enables public agencies to avoid execution errors, which we maintain needs to be considered for efficient risk management. Risk management should comprise the development of capabilities for improving the efficacy of feedback learning in the context of SBIR/PCP, thereby corroborating that the materialization of the benefits of R&D investments approached as real options requires skills and routines (McGrath and Nerkar, 2004; Vanhaverbeke *et al.*, 2008). Amplifying pre-investments can mitigate both technical uncertainty (relative to the funded projects, i.e., the supply) and organizational uncertainty (relative to the public organization, i.e., the demand) either before the SBIR/PCP cycle through basic R&D public funding, or during the SBIR/PCP cycle itself.

An attention-augmented real options approach to public sector heterogeneity can help public agencies transcend the usual impediments they face in the context of SBIR/PCP. As rightfully expressed by Mergel and Desouza "the standard operating procedure for the acquisition of innovations in the public sector is a bureaucratic contracting process that involves specifying a detailed request for proposals, a cumbersome selection process, and messy contract negotiations" (2013, p.888). In the case of SBIR/PCP, public agencies (and their managers) need to embrace diverse solution providers without necessarily being able to anticipate whether the solution will be suitable or implementable, thus making evident their bounded rationality, which can in turn reduce the adoption of innovations in some public agencies. We suggest that "expectations, framing, contractual and legal statements (…) that have been codified as organizational knowledge in handbooks and operating manuals" (Ibid. p.738) participate in feeding organizational risk within public agencies under the pretext of ensuring accountability and risk reduction for public managers. The acquisition of deep technical knowledge and feedback learning capabilities can be usefully leveraged in exploratory SBIR/PCP programs funding small demonstration projects, for gaining political

backing and overcoming the "the barriers, time and cost to reconfigure existing knowledge and to understand the challenges associated with large scale" (Edler *et al.*, 2015, p.102).

CONCLUSION

Like their private counterparts, public agencies also need to take into account behavioral factors in the strategic management of R&D investments (Vanhaverbeke *et al*., 2008) for the potential value of a real option to materialize in realized value (Barnett, 2005). Our attention-augmented real options approach takes into account the specific attentional constraints encountered by public managers due to the high transaction risks pertaining to the strong asset specificity of public R&D investments relying on externally distributed intelligence and the broadness of public value. We contribute to the theory of real options by grafting behavioral biases in an attention-augmented real options approach (Barnett 2005; Leiblein *et al.*, 2017; Posen *et al.*, 2018) that conceptualizes the bi-directional linkages between real options and the heterogeneity of organizations (Trigeorgis and Reuer, 2017) in the context of the public sector. We first reflect on how the learning space for real options can emerge from the heterogeneity of public agencies, defined as the openness of their attention structures, before reversing the relationship by considering that the strategic management of the learning space for real options can increase the quality of their feedback learning processes, with corresponding effects on that same heterogeneity.

We illustrate our framework in the context of the SBIR/PCP programs, as public sequential investments aiming at selecting and managing a portfolio of external emerging technologies as real options that either the public or the private sector can exercise at some predetermined date (Vonortas and Hertzfeld, 1998). Our recommendations, grounded in a behavioral real options understanding of the different types of uncertainty affecting R&D portfolio selection and management by public agencies, aim at moving away from the traditional criticism around the public sector's assumed risk aversion. Understanding the

effects and the strategic management of R&D investments in terms of an attention-augmented real options approach can provide public managers in charge of SBIR/PCP programs with a strategic management tool for conducting the selection and management of their portfolios of projects. Effective risk management can benefit from the consideration that behavioral biases may lead to execution errors in the different phases of the SBIR/PCP cycles, and target alleviating mechanisms for promoting feedback learning processes, leading to de-biasing the successive valuation analyses of real options (Smit and Kil, 2017). We finally contribute to broadening the notion of entrepreneurial risk in the context of the public sector. Originally defined as "the a priori uncertainty that the funded research will result in a commercialized product, process or service" (Link and Scott, 2010 p.590), we underscore that prospective uncertainty alone cannot account for entrepreneurial risk in public agencies. It is also the product of attentional constraints feeding contemporaneous uncertainty by introducing behavioral differentiation at all stages of the selection and management of a portfolio of options, which substantiates our attention-augmented real options approach to public R&D investments.

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