DECLARATION FOR THE PhD THESIS

The undersigned

SURNAME	LAUREIRO MARTÍNEZ
NAME	DANIELLA
Registration number	P1194679

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Date: 31st of January 2011
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Table of Contents

Introduction

This dissertation seeks to contribute to uncover the cognitive and neuropsychological foundations of strategy. I take an attention modulation perspective to understand how decision-making processes differ among individuals.

In particular, I examine the following research questions: ‘How do attentional processes impact strategic decision-making?’, ‘Why some individuals show more cognitive flexibility than others and how does that impact the strategic decisions they make?’, ‘What are the cognitive origins of routines?’, ‘What are the neuropsychological foundations of individuals’ ability to search for innovative solutions?’.

This dissertation intends to achieve its objective through theoretical and empirical interdisciplinary analysis.

I mainly draw from two streams of theory. First, from the organizational literature about attention (Ocasio 1997), routines (Nelson and Winter 1982, Cohen and Bacdayan 2004), strategic decision making (Hickson et al. 1986, Eisendhardt and Zbaracki 1992), and ambidexterity (Gupta et al. 2006, March 1991, Mom et al. 2007, Raisch and Birkinshaw 2008). Second, from the neuropsychological literature on high-level cognitive functions that deal with attention control and thus allow individuals to be cognitively flexible and balance their behavior (Aston-Jones and Cohen 2005, Norman & Shallice 2000, Posner 1990, Ravizza and Carter 2008).

From a research design standpoint, I combined methods and tools from three related fields: strategy, managerial cognition and neurosciences. I blend different methods: verbal protocol analysis, neuropsychological tasks, simulated managerial decisions and brain imaging studies.

The data I rely on are generated through two studies on different samples of individuals. In the first study (involving 89 master students) I used questionnaires and neuropsychological tests. In the second series of studies (involving 75 expert decision makers, i.e. 25 entrepreneurs, 25 innovators and 25 managers) I combined a battery of neuropsychological tests, functional magnetic resonance imaging (fMRI), verbal protocol analyses (VPA), simulated innovation decisions, genetic material and questionnaires.

This dissertation is divided into three papers. In the first paper I developed the theoretical propositions that lie at the basis of solving a strategic decision-making dilemma as is the exploration-exploitation dilemma but that could eventually be applied to the strategic situations in which the balance between exploiting known sources of reward needs to be balanced with exploring possible better –but less certain- sources of reward. In this paper, based on recent findings from the cognitive neurosciences, I derive propositions that need to be tested and suggest possible ways to do so.

In the second paper I rely on neuropsychological tasks and a decision-making simulation to study how less-mindful abilities –as routinization- blend with mindful abilities –as cognitive control capabilities- to impact decision-making performance measured using a task that needed the participant to solve the innovator's dilemma. My findings illustrate how differences in cognitive control capabilities, i.e. an individual's ability to regulate one's attention modulation processes, influence decision-making performance. I show that high performance in a decision making task is obtained when superior cognitive control capabilities (CCC) are combined with high levels of routinization of the decision-making process. Also, the data shows a mediating effect of routinized decision-making between CCC and performance; routinization is therefore a function of superior attention control and directly influences the performance of innovation decisions. Thus, there is no contradiction between routinization and innovation.

In the third paper I rely on functional magnetic resonance imaging of the neural activity of two groups of expert decision-makers (i.e. managers and entrepreneurs). I again study how their ability to routinize and their cognitive control capabilities both impact decision-making performance measured using a task that needed the participant to solve the exploration-exploitation dilemma. Results point to robust and significant differences among groups. First, I found significant differences in the neural activations associated with explorative and exploitative decisions. Second, and crucial, even though there were no significant differences in the total number of times that the group of entrepreneurs and the group of managers chose to explore or exploit, there were significant differences in the neural activation patterns of each group. The entrepreneurial group shows significantly stronger activations in fronto-parietal regions as well as of the locus coeruleus (Aston-Jones and Cohen, 2005). This may reflect more efficient mechanisms of cognitive control when overcoming exploitative drive in order to explore alternative options. An important additional contribution lies in the fact that, to my knowledge, no studies have addressed neuropsychological origins of decision-making differences in performance in a mature, experienced population of leaders who are held accountable for real decision outcomes in their organizations.

I expect this dissertation work will contribute to four possible streams of literature.

First, to the literature that deals with the cognitive and behavioral mechanisms behind strategic decision-making. In particular, I expect the findings of the second paper to contribute to move the dilemma of mindful versus less-mindful (e.g. Levinthal and Rerup 2006, Weick and Sutcliffe 2006) to an integrated understanding that blends the two together.

Second, I expect the findings that suggest possible antecedents for routinized behaviour to contribute to the broader literature on organizational learning and change by providing an answer to questions such as where do routines come from (e.g. Nelson and Winter 1982, Becker 2009)

Third, I expect that the findings on cognitive flexibility and the inter-individual differences in the ability to swith attention will help understanding how individuals help organizations in overcoming inertia, developing new Business models and thus facilitating strategic renewal and innovation strategies (e.g. Christensen 1997, Tripsas and Gavetti 2000)

Finally, the findings related to entrepreneurs superior ability to switch the focus of attention and thus their behavior may help in understanding the origins of entrepreneurs' ability to switch 'cognitive style' (e.g. Baron 2004, Baron and Ensley 2006) and thus understanding the individual abilities required to identify opportunities and enact them.

The future research that derives from this dissertation will focus on at least three avenues for development.

First, I want to gain an integrated understanding of the different sources and of information and methods that I collected during my dissertation work. In particular, I would like to integrate to the results of the brain imaging studies and the neuropsychological test also the results of the Verbal Protocol Analysis – VPA. The VPA has proven as a very useful methodology for uncovering the cognitive processes lying behind problem solving (Ericsson 2003). Participants were given a short ill-structured problem and are asked to freely "think out loud" during the solution process. Their answers were recorded and their verbalized solutions can be coded and statistically analyzed. I have collected the VPA for a group of 28 managers, a group of 25 entrepreneurs and an additional group of 12 decision-makers in an innovative organization in the microelectronics industry.

A second point of future work will be the validation of the robustness of my current findings, exploring the micro processes that constitute cognitive flexibility or, conversely, that facilitate the formation of cognitive inertia, in innovation processes.

From a methodological standpoint, I look forward to achieve robustness in my findings by continuing blending different methods.

Finally, an ambitious but certainly crucial and relevant future goal that I look forward to work on consists on the development and application of insights useful to teach managers and entrepreneurs develop the cognitive abilities that significantly impact the performance of their innovative decision-making. Strategic decisions made by leaders have far-reaching consequences. Therefore it is of great importance to understand not only how such decisions are made but also how they can be improved. I am currently involved in a project that derived from my dissertation and that aims precisely at developing an understanding of what are the possible interventions that may allow to improve the type of cognitive capabilities that I have found to be relevant for strategic decision making.

I hope you find this work useful and that you enjoy reading this dissertation as much as I enjoyed working on it!

The Neuro-Scientific Foundations of the Exploration-Exploitation Dilemma.

Daniella Laureiro-Martínez

Stefano Brusoni

Maurizio Zollo

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ABSTRACT

What are the origins of the ability to continuously explore novel domains of activity while at the same time exploiting the current knowledge base with increasing efficacy? The conflicting objectives of exploration and exploitation compete for scarce resources, among which managerial attention is possibly the most critical. This paper integrates recent findings on the neuromodulation of attention to provide a foundational step in understanding how the mind of the manager handles the exploration-exploitation dilemma. Also, this paper proposes several possible ways to combine research in neuroscience, psychology and management to advance our knowledge of the microfoundations of managerial decision-making.

1 INTRODUCTION

Adaptive firm behavior in a diverse and rapidly changing environment requires a trade-off between exploiting known sources of reward and exploring the environment for more valuable or stable opportunities. This trade-off is known as the exploration-exploitation dilemma (March, 1991) and is present at different levels of analysis and different time scales of decision-making. There is no general optimal policy for how to manage the trade-off between exploration and exploitation in non-stationary environments (Cohen et al. 2007).

From a managerial point of view, the exploration-exploitation dilemma, which is key to many of the challenges faced by organizations, refers to the difficulty faced by organizations and their members in trying to find a balance among competing activities in the context of scarce resources – the need to be efficient to get the most from a current situation, while at the same time exploring possibilities for future improvements. As March (1991) puts it:

> Adaptive systems that engage in exploration to the exclusion of exploitation are likely to find that they suffer the costs of experimentation without gaining many of its benefits. They exhibit too many undeveloped new ideas and too little distinctive competence. Conversely, systems that engage in exploitation to the exclusion of exploration are likely to find themselves trapped in suboptimal stable equilibria. As a result, maintaining an appropriate balance between exploration and exploitation is a primary factor in system survival and prosperity. (March 1991)

Levinthal and March (1993) similarly argue that “an organization that engages exclusively in exploration will ordinarily suffer from the fact that it never gains the returns of its knowledge” and that “an organization that engages exclusively in exploitation will ordinarily suffer from obsolescence” (p. 105). A narrow search can lead to increasingly rigid cognitive maps and highly specialized competencies that may become core rigidities (Leonard-Barton 1995). The so called “ambidexterity hypothesis” (Tushman and O’Reilly 1996) states that the higher the organizational ability to balance exploration and exploitation, the higher the organizational performance.

Since March’s (1991) seminal article, the management literature has used the terms “exploration” and “exploitation” in studies of organizational adaptation, organizational learning, competitive advantage, technological innovation, organization design and organizational survival. However, “an examination of the literature indicates that the answers contained there to the central questions on this subject remain incomplete, at times contradictory, and at best ambiguous” (Gupta et al. 2006). The review in Section 2 shows that while the exploration-exploitation literature is extensive and growing, there are gaps that we believe derive from a lack of understanding of the dilemma at the micro level, i.e. the individual decision-makers’ point of view. There is an intriguing opportunity to better understand this point of view. The recent development of knowledge in the cognitive neurosciences opens, in fact, exciting possibilities to build integrative approaches to understand organizational dilemmas from a micro perspective. That is the overarching objective in this paper: to explore an organizational conundrum from an individual level of analysis, showing how interpersonal variation in the decision-maker’s neurological disposition affects the decisional outcomes and, potentially, the performance of a given task connected to that decision.

To do so, the paper is organized as follows: Section 2 briefly presents the main gaps in the organizational literature on exploration-exploitation, focusing on the one that this paper aims to contribute to; Section 3 addresses the microfoundations – i.e. the individual origins – of this dilemma, whereas Section 4 contributes by bridging with neuroscience and discussing certain findings in that domain that may help to clarify the roots of the managerial dilemma and suggest ways to cope with it. We then provide an illustration of how the theory we developed might explain the behavior and the outcomes connected to one of the most famous innovators of modern times: Thomas Alva Edison. Section 6 then presents the main challenges involved in the development of an empirical agenda to validate these ideas, offering a full set of suggestions on how to tackle them, and Section 7 concludes with several suggestions for the development of this line of work in future research.

2 GAPS IN THE MANAGEMENT LITERATURE ON THE EXPLORATION-EXPLOITATION DILEMMA

A review of the literature on the exploration-exploitation managerial dilemma uncovers several limitations and gaps, which we briefly cover with the aim to focus on and potentially contribute towards resolving one particular gap: variation among individuals in the tendency to respond in an exploitative or explorative way to a given stimulus, and on the ability to shift their responses according to changes in the environmental conditions, have not been explored..

A central gap is that most of the extant research focuses on the structural antecedents to and the effects of involvement in exploration and exploitation on firm performance (Raisch and Birkinshaw 2008). Few studies delve more deeply into *how* these two activities occur simultaneously. Of course, part of the *how* question has to do with the actual capacities and behaviors of *individual members of the organization*, rather than with organizational arrangements and collective processes. Another key gap is the lack of clarity about the levels of analysis in research on exploration-exploitation. Recent theoretical contributions (Felin and Foss 2005; Felin and Hesterly 2007; Rothaermel and Hess 2007) identify two main problems with the single-level research approach. First, focusing on only one level of analysis implicitly assumes that most of the heterogeneity is located at that level while other levels are more or less homogeneous. Second, this focus implies that this level is independent of interactions with other lower- or higher-order levels of analysis.

Another main concern with the current literature is the lack of agreement about key elements regarding the definitions of exploration and exploitation. It is not clear from the literature whether exploration and exploitation should be viewed as two ends of a continuum, or as two different and orthogonal aspects of organizational behavior. The central ambiguity in the definitions is whether exploration and exploitation differ in the type of learning or by the presence/absence of learning (Gupta et al. 2006). Table 1 summarizes some of the definitions that appear in key articles on the subject.

[INSERT TABLE.1 ABOUT HERE]

In order to avoid confusion, in this paper we adopt a definition very close to the one provided in neuroscience (discussed in Section 4) that admits learning in both exploration and exploitation. We define exploration as the behavior that includes search for alternatives and disengagement from the current task. The simplest form of exploration is random search but other more structured types of search, such as the use of heuristics or explicit algorithms, are also included. As a consequence of this behavior, experimentation, flexibility, discovery and innovation are shown. We define exploitation as the behavior that helps optimize task performance. When this behavior is present, there is a high engagement with the current task. As a consequence of this behavior, selection, refinement, choice, production and a concern with efficiency are shown.

The fourth major gap in the received literature on the exploration-exploitation dilemma, and the one we focus on, concerns the role of the characteristics of individual traits as mechanisms underpinning the development of organizational capabilities related to the balanced management of exploration and exploitation activities. The roles of individual and group characteristics were viewed as an important and necessary focus of scholarly attention since the inception of the behavioral theory of the firm (Cyert and March 1963; March and Simon 1958; Simon 1985). March (1991), for example, describes the cognitive limits that individuals encounter when trying to conduct explorative and exploitative processes simultaneously. And Tushman and O'Reilly (1996) argue, the ability to explore-exploit at the organizational level is facilitated by the top-management team's internal processes.

It is only recently, however, that scholars have started to empirically investigate team characteristics that enable organizations to manage both exploration and exploitation (Beckman 2006; Lubatkin et al. 2006; McKenzie et al. 2009; Mom et al. 2009; Perretti and Negro 2006; Smith and Tushman 2005). Gibson and Birkinshaw (2004), for example, note the "important role played by senior executives in making an organization context effective and developing ambidexterity" (p. 223). Similarly, Smith and Tushman (2005) explore the integrative mechanisms by which leadership teams might successfully manage the contradictions that arise from structural separation in ambidextrous organizations, and Volberda, Baden-Fuller and Van Den Bosch (2001) note that "top management explicitly manages the balance of exploration and exploitation by bringing in new competencies to some units while utilizing well-developed competencies in others" (p. 165). And at the group level of analysis, Beckman (2006) finds evidence that the composition of the founding team, and members' prior company affiliations in particular, is an important antecedent to firms' exploitative and explorative behaviors.

Unfortunately, the focus on team characteristics as the antecedents to the development of organizational capabilities in ambidexterity is not matched by studies on the role of managers' individual characteristics or on the ability to make balanced exploration-exploitation decisions. O'Reilly and Tushman (2004), for instance, emphasize the role of ambidextrous managers executives with "the ability to understand and be sensitive to the needs of very different kinds of businesses" (p. 81). Despite a seeming consensus on the importance of the individual, the state of the art in scholarly work on the individual level of analysis shows a concerning paucity, with the notable exception of Mom et al. (2007). In our view, this is an important concern, as many current 'holistic' explanations might capture at least some of what really are effects of variation at the individual level of analysis (Felin and Foss 2005; Felin and Hesterly 2007). We explore this further in Section 3.

3 THE EXPLORATION-EXPLOITATION DILEMMA IN THE MANAGER'S MIND

Most studies of exploration-exploitation, starting with March's (1991) seminal work, focus on levels of analysis above the individual. March (1991) analyzes the exploration-exploitation trade-off in the social context of organizations, focusing on two distinctive features: mutual learning in the organization and the individuals involved, and the competition for primacy among organizations. Implicit in his model is the assumption that the balance between exploration and exploitation is based on a turnover process among a mix of individuals with different cognitive characteristics (some more inclined to exploration, others more inclined to exploitation), who achieve a trade-off for the whole organization.

The mechanism based on the turnover of "cognitively specialized" (and inflexible) managers to achieve a balance between those predisposed to exploitative behavior and those predisposed to explorative behavior, however, is clearly not the only one at the disposal of the organization (the alternative, of course, is to gather a group of managers who can think and act in both modes with relative ease), and probably not even the optimal one. First of all, having a group of cognitively specialized decision-makers will simply turn the decision into a political battle between the two factions, with results driven by the relative size and political weight of the two factions, rather than to rational choice. Second, even when the decision can be efficiently allocated to “exploration-minded” or to “exploitation-minded” managers, this decision itself requires a decision-maker (e.g. the CEO) with a significant amount of cognitive flexibility to recognize the advantages and disadvantages of the two alternative allocations of the decision-making responsibility. Essentially, the problem (and the solution, via cognitive flexibility) would still be there, but would be upgraded to the cognitive profile of the person at the top of the organization, who assigns the problem to the cognitively specialized groups.

The alternative scenario of having cognitively non-specialized (and flexible) managers might thus be superior to the one described above, since it would reduce the likelihood of political fights and sub-optimal decisions and would not require the presence of a “higher order” decision-maker to assign the responsibility of the solution to “cognitively specialized” groups of managers. As O’Reilly and Tushman (2004) recognized, “one of the most important lessons is that ambidextrous organizations need ambidextrous senior teams and managers” (p. 81).

We thus propose that to achieve a better understanding of how both exploration and exploitation can be conducted, we need an in-depth examination of the microfoundations of organizational learning. The micro – individual – level of analysis may in fact account for an important amount of heterogeneity in decisional and performance outcomes, and should be explicitly studied:

> *to fully explicate organizational anything – whether identity, learning, knowledge or capabilities – one must fundamentally begin with and understand the individuals that compose the whole, specifically their underlying nature, choices, abilities, propensities, heterogeneity, purposes, expectations and motivations. While using the term 'organizational' may serve as helpful shorthand for discussion purposes and for reduced-form empirical analysis, truly explaining the organization (e.g. existence, decline, capability or performance), or any collective for that matter, requires starting with the individual as the central actor. (Felin and Foss 2005)*

Mom et al. (2007) were, to the best of our knowledge, the first to analyze the exploration-exploitation dilemma at the individual level of analysis. They explored the influence of knowledge flows on the manager's explorative or exploitative activities, recognizing that one of the most promising avenues for future research is "measuring exploration and exploitation at the managerial level of analysis using objective measures" (p. 927).

Along these lines of discourse, Section 4 discusses recent findings on the neuromodulation of attention, which, we argue, is at the core of the human ability to shift from one learning mode to another. We provide some suggestions on how to build on the concepts of situational uncertainty, utility perception and attention focus to further investigation of organizational exploration and exploitation.

4 A NEUROSCIENTIFIC APPROACH TO THE EXPLORATION-EXPLOITATION DILEMMA

In line with our aim to examine the microfoundations of the exploration-exploitation dilemma, we searched for work on the cognitive processes underlying the exploration-exploitation trade-off. Recent work on the neuromodulation of attention proposes that interactions between the orbitofrontal cortex (OFC), the anterior cingulate cortex (ACC) and the locus coeruleus (LC) (see Fig.1) may modulate attention and thus balance exploration-exploitation (Aston-Jones and Cohen 2005; Cohen et al. 2004; Usher et al. 1999).

[INSERT FIG.1 ABOUT HERE]

Traditionally, the locus coeruleus-norepinephrine (LC-NE) system was considered to be implicated solely in arousal. However, multiple recent findings suggest that this system plays a more complex and specific role in the control of behavior by contributing to the optimization of behavioral performance (Sara 2009).

Aston-Jones, Rajkowshi, Kubiak and Alexinsky (1994) observe that the LC shifts between two operating modes: the phasic and the tonic. In the former, LC cells exhibit phasic activation in response to the processing of task-relevant stimuli, but display only a moderate level of tonic discharge. This mode is consistently associated with enhanced attention focus, generating “exploitative” behavior, defined as behavior that optimizes and achieves high levels of task performance (Aston-Jones and Cohen 2005). It is important to note here that the analysis is at the individual level. Exploitative behavior translates into a high level of engagement with the current task. As a consequence, behaviors that show refinement in the selected actions and a concern for efficiency are demonstrated.

In the tonic mode, LC cells do not respond phasically to task events, but exhibit higher levels of ongoing tonic activity. Exploration is defined as the behavior shown when there is search for alternatives and disengagement with the current task (Aston-Jones and Cohen 2005). This mode is associated with explorative behavior because it corresponds with poor performance on tasks that require focused attention, and with increased distractibility. The simplest form of exploration is random search, but exploration also includes more structured types of search, such as the use of heuristics or explicit algorithms. This behavior demonstrates abilities for experimentation, flexibility, discovery and innovation.

It should be noted that the definitions of exploration and exploitation provided by neuroscientists (Aston-Jones and Cohen 2005) are compatible with those in the management literature (see Table 1) and with March's (1991) definition: "The essence of exploitation is the refinement and extension of existing competences, technologies, and paradigms. Its returns are positive, proximate, and predictable. The essence of exploration is experimentation with new alternatives. Its returns are uncertain, distant, and often negative" (p. 81).

The findings on the functioning of the LC and its consequent type of behavior are based on two pieces of evidence. The first comes from experiments on monkeys, which transitioned from a phasic to a tonic mode and then reversed when the new target was identified. This transition requires that LC has the relevant information to determine when to switch between phasic and tonic modes, an important aspect that we address in the section on perception of utility (Usher et al. 1999). The second piece of evidence derives from studies of humans measuring pupil diameters – a good proxy for LC activity – and functional Magnetic Resonance Imaging (fMRI) experiments (see (Beversdorf et al. 2002; Daw et al. 2006; Sterpenich et al. 2006) among others). Usher and colleagues (1999) also develop a biophysically plausible model of LC functioning that accounts for transitions between the phasic and tonic modes in terms of a single physiological variable (coupling between LC cells) and explains the impact of these shifts on task performance. In brief, the model suggests that the phasic mode favors exploitation by releasing norepinephrine (NE) when a task-relevant event occurs, thereby facilitating the processing of that event, while sustained release of NE in the tonic mode indiscriminately facilitates the processing of all events irrespective of their relevance to the current task, thereby favoring exploration.

Viewed from the perspective of attention, the LC phasic mode supports the current control state (exploitation), while the LC tonic mode provokes a withdrawal of control from the current task, favoring the sampling of other behavioral goals (exploration). These changes between phasic and tonic modes are the basis for an understanding of the exploration-exploitation dilemma from an attention perspective. When the utility derived from a given behavior is low in comparison to expectations, flexibility to change the attention focus, and thus the behavior from exploitation to exploration, is needed to explore the environment and sample different behaviors until new sources of reward are discovered. This is the role played by different modes of activity in the LC-ACC/OFC system. Aston-Jones and Cohen (2005) observed that the LC shifts between two distinct operating modes, and that these shifts change attention and then behavior. The LC phasic mode supports the focus of attention on the current control state (exploitation), while the LC tonic mode provokes a withdrawal of control from the current task, thus favoring broader attention and the sampling of other behaviors (exploration)[1]. The phasic LC responses facilitate context-congruent behavioral responses (exploitation) and the tonic mode of LC facilitates sensitivity to different stimuli and the execution of a broader class of behavioral responses (exploration).

These neuroscientific findings on changes in attention scope contribute to our understanding of the management exploration-exploitation dilemma from an attention perspective. The idea that broad attention is important in situations that are dynamic, ill-structured, ambiguous and unpredictable is acknowledged in the management literature (Levinthal and Rerup 2006b; Weick and Sutcliffe 2006). In the opposite scenarios, the economies of narrow attention are more appropriate and, through their reliance on routines, can be cost-efficient (Nelson and Winter 1982). As a consequence, the higher the uncertainty in a situation, the higher the likelihood that broad attention – and thus explorative behaviors – will lead to better performance.

However, these explanations still leave out the important question of what information the neural system uses to determine whether it should exploit (LC phasic mode) or explore (LC tonic mode). Studies have found that the brain computes the

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[1] We should note here that, whereas we have described the phasic and tonic modes as distinct, they likely represent the extremes of a continuum of function. For expository purposes it is more useful to distinguish them at the two extremes.

perceived utility in a particular situation, compares that with its expectation levels, and drives shifts between LC phasic and tonic modes by influencing simple physiological parameters (Usher et al., 1999). When low expected utility is perceived, the broad mode of attention (tonic mode of the LC functioning) is activated. When high utility is perceived, the focused mode (the phasic LC mode) is activated. Studies of humans (and neuronal records in primates) show that the frontal cortex plays an important role in the evaluation of utility. Different areas of the brain are found to be related to the assessment of rewards and costs. A large number of neuroimaging studies, involving diverse experiments, have examined brain responses to reward stimuli. They consistently identify a common set of neural structures that are activated in response to these stimuli, mainly the OFC, the ventral striatum, and the ventromedial prefrontal cortex. The OFC has been implicated in hedonic experience across all sensory modalities (Rolls 2000). Of specific interest are areas in the striatum and the OFC that are particularly responsive to rewards and which change, accumulate, or are learned over time (Knutson et al. 2003; Koepp et al. 1998; Murray et al. 2007).

Attempts have also been made to identify the brain areas activated by cost-related issues. The anterior cingulate cortex (ACC) is traditionally considered to be directly responsive to aversive interoceptive and somatosensory stimuli, and particularly to pain (e.g. (Peyron et al. 2000). Recent neurophysiological studies on monkeys and on humans have consistently demonstrated that ACC is strongly responsive to negatively valenced information, such as performance errors, negative feedback, monetary losses and even social exclusion (Eisenberger et al. 2003), and also to task difficulty and decision-making conflicts (Botvinick et al. 2004). Therefore, there is much evidence to suggest that the OFC is involved in reward evaluation, whereas the ACC is responsive to a variety of negatively valenced signals (Aston-Jones and Cohen 2005; McClure et al. 2004; Montague et al. 2006; Tom et al. 2007). These results point to the existence of a strong relationship between situation uncertainty and utility perception. Thus, risk-averse individuals, all else being equal, will find higher utility in less uncertain situations and, as a consequence, will act under the phasic LC mode, showing more exploitative behavior. In highly uncertain situations, the opposite will occur. Individuals will find less utility in such situations and will shift to a tonic LC mode, acting in a more explorative way.

That perceiving a high utility reduces the attention to search and exploration, and that the perception of low utility promotes search and explorative behavior, are fundamental tenets of the behavioral school (Cyert and March 1963; March and Simon 1958), a departure from standard neo-classical thinking, which assumes constant investment in search and exploration, independent of the current task. The “satisficing” behavior assumption has been widely tested in and supported by management studies over the decades (see (Grève 2003), for a recent review), and by evidence on the impact of past performance on investment in attention and learning by firms (Bateman and Zeithmal 1989; Simon et al. 2000; Thomas et al. 1993).

Additionally, the perception of uncertainty has been proposed as an important factor affecting the evaluation of a given situation (McClure et al. 2006; Yu and Dayan 2005). It seems that our brains distinguish between expected and unexpected uncertainty. Two important neuromodulators – acetylcholine (ACh) and norepinephrine (NE), respectively – signal expected and unexpected sources of uncertainty. When exploiting, if prediction errors are higher than expected, the current strategy should be revised and we should explore. If, on the contrary, the prediction errors can be accounted for in terms of expected uncertainty, the exploiting strategy should be maintained. In general, taking into account that individuals are risk-averse, then the higher the unexpected uncertainty perceived in a situation or a problem, the more difficult it will be for the individual to understand the outcome of the situation/problem and so the less the utility from the situation.

The neuroscientific findings summarized above provide the basis for an understanding of what underlies the exploration-exploitation dilemma. These findings also help to bridge some of the gaps described in Sections 2 and 3. The neuroscientific definitions of exploration and exploitation, and the discovery of the neurological mechanisms underlying the shift between the two attentional states, help to resolve the debate over whether exploration and exploitation are to be viewed as positions on a continuum or as orthogonal situations. At the individual level of analysis, they are clearly orthogonal, since at any given moment an individual cannot be in both the phasic and tonic modes of LC functioning. At the organizational level, however, members of a group of individuals might be functioning in different modes, which means that the group overall will be working on a continuum between a completely phasic mode (all focused on the current task, i.e. purely exploitative mode) and a completely tonic mode (all focused on exploration). Of course, any group typically works at a position on the continuum located somewhere between the two extremes, but this position is important to the prediction of collective behavior (see Fig. 2). Importantly, the (discrete) shifts in LC operating modes of individuals in the group over time will cause the group position on the continuum to constantly shift.

[INSERT FIG.2 ABOUT HERE]

In the next section, we offer a managerial illustration of how these neurological mechanisms might influence the activities of groups involved in R&D work.

5 EXPLORATION-EXPLOITATION AND THE "WIZARD OF MENLO PARK"

How are the ideas presented in this paper reflected in a real case? In this section, we argue that an organizational process of strategic relevance, such as a product innovation process, can be decomposed in sub-activities (explorative-exploitative behaviors) that are largely influenced by a decision-maker's attention focus (broad and narrow), which we expect to in turn originate from neuromodulatory mechanisms guided by the LC.

We will exemplify the ideas we propose using the well-documented case of Thomas Alva Edison – one of the most famous inventors of all times – and the main events in one year of work on the microphone at Menlo Park, one of the first facilities entirely dedicated to R&D activities. Edison serves as a good case for illustrating the ideas presented in this paper relating to micro- and macro-levels of analysis since he was not the “lone genius” but instead a “collective noun and means the work of many men” (Lindgren, 1979, p.17 cited in Swedberg, 1993). While Edison was clearly at the head of the Menlo Park operations, they were the result of the collaboration and work of many individuals: the Park “apparatus” served to promote a huge number of inventions (“a minor invention every ten days and a big thing every six months or so” (Lindgren, 1979, p.17 cited in Swedberg, 1993)), generating more than 400 patents in its 6 years of operation. There is agreement on the fact that Edison was a relentless innovator or, closer to our argument, a “meta inventor”. He made Menlo Park the cornerstone of modern industrial research. The Park was the first industrial laboratory concerned with both creating knowledge and controlling new knowledge application. It is interesting to apply the ideas we have integrated so far to the context of an R&D lab, where not only research was done and many new inventions were discovered, but also the development, polishing, protection and selling of the inventions was done.

Menlo Park demonstrated the ability to successfully combine both explorative and exploitative activities. Different inventors inside Menlo Park were involved in both explorative and exploitative activities, with Edison leading their work in *both* cases. Edison’s high involvement in the different activities in Menlo Park may have had some negative consequences for the development of the incubator. On the other hand, his role exemplifies how the way that leaders attend to the particular problems of the innovation process, facing the different decisions required to handle both explorative and exploitative challenges, contributes to the success of the overall innovation process.

Not only was Edison working on many different projects at once, requiring different modes of operation in his attention system, but he also showed the ability to continuously shift between the two cognitive modes within the context of a single process. On the one hand he could be very focused on advancing knowledge development towards the solution of a very specific problem. On the other hand, he also recombined specialized knowledge from different fields to generate new, broader sub-fields and more general knowledge.

How did he switch from one mode to the other? In different innovation cases there is evidence of the importance of specialization as domain-specific expertise(Kaufman and Baer 2006). Specific expertise is usually the foundation for building innovation. In addition, however, in Edison's case (as in other cases studied by Kaufman and Baer), general expertise played a key role, along with the ability to recombine knowledge from different fields, or to apply it from one field to another. As stated by Hargadon and Sutton (2000), Edison and the people in his lab had the ability to "move easily in and out of separate pools of knowledge, to keep learning new ideas, and to use ideas in novel situations" (p. 161). Like Bell, Morse, Ford and others, Edison did not advance science in the way specialists do. These scientists instead focused on and developed an in-depth knowledge about the specific issues (problems, components, etc.) of their inventions, while also broadening and bringing different streams of scientific discoveries into practical devices and systems (Skrabec

2006). These serial innovators were sometimes able to *explore*, broaden their attention, be creative, recombine and bring together different ideas and also *exploit*, narrow down their attention, concentrate and focus on solving a specific problem.

To illustrate, a detailed study by Carlson and colleagues (Carlson, 2003, p. 155-156) shows how Edison's work on the microphone (the carbon button transmitter for the telephone) can be summarized as a series of contrasting behaviors in which "During certain periods, Edison varied his lines of research, and then at particular moments, he appears to have selected one line for further development" (p.156). His inventive patterns can be seen as characterized by "explorative" periods (when he played out different lines of investigation) following by "exploitative" periods when he selected and focused by either choosing one of the lines or by recombining the most promising lines.

Figure 3 summarizes the main activities Edison undertook while developing the microphone for the telephone during 1877. The ovals show the moments when he chose which line to proceed with (Diagram adapted from Carlson, 2003, p. 156). For example, in late April 1877, Edison was experimenting with different lines (i.e. dragging, rubbing, etc.). He then chose to focus on one option (i.e. the pressure tekephone) to further improve it. Again, in September of that year, after having experimented with different production models (i.e. resonance, reed, etc.), he decided to focus on one option. In this case he did not actually chose one, instead combining the most promising results from different lines and focusing on developing a rubber tube production version.

[INSERT FIG.3 ABOUT HERE]

As documented in Carlson (2003, p. 152) this particular situation can be analyzed as a specific case in point:

> "Edison or his associate James Adams substituted points of plumbago (i.e. graphite) for the disks on his "squeeze" telephone. These telephones seemed to work better than previous versions, leading Edison to think more carefully about using points. In particular, he now considered using four high-resistance points pressing on the diaphragm with varying degrees of force. Edison noted an inverse relationship between the mechanical force and the electrical resistance that the resistance increased as the force decreased- and drew on this observation to construct a pressure telephone in April 1877."

A schema for interpreting this example in the light of the ideas proposed in this paper is presented in the Figure 4. The concentric ovals signal the different sublevels at which the exploration-exploitation dilemma can be seen in the telephone example. At the center we present the more micro level we have included in our ideas (the LC mode), and the most external oval represents the more macro level we have presented (the behavior at the organizational level). In the telephone example, Edison started with an exploratory behavior searching for alternatives (in this case five different ones) and experimenting (adding the graphite points). Edison got positive feedback from the environment, obtaining a good outcome (better working telephones), which increased the utility and lowered the uncertainty he perceived in the problem at hand. Perceiving a higher utility, the focused mode of LC functioning (phasic) arose (see first central box to the left). Edison started focusing his attention ("think more carefully about using points…" p.156) on one alternative to improve it. He narrowed down from 5 alternatives to the apparently best one to further exploit the idea, develop and improve it ("he chose to drop four lines in favour of the pressure line" p.156).

[INSERT FIG.4 ABOUT HERE]

This shifting between exploring and exploiting was repeated several times in the telephone invention and in several others. As can be seen in Fig.4, as a result of the "squeezing" alternative, Edison focused his research on the pressure telephone. His shifts between exploring and exploiting continued during the summer of 1877 (in Fig.4 see the box beginning with "not convinced"). After deciding to focus on the pressure telephone, Edison and his associates faced a different problem: the quality of the acoustic components was not satisfactory for them (low utility perceived). Consequently, he decided to undertake a search for better components (perceiving a low utility, he was under the tonic LC mode and so broadened his attention). The lab then extended their investigation to different acoustic components (material search, diaphragm, resonance cavity, reeds, springs, fluff) that were studied and tested (explorative behaviors). Once higher standards were reached (and so a high utility perceived) again a narrowing-down process appeared in which Edison combined the most promising results from the different lines of research to create the rubber tube production version of the telephone.

If we think about applying the schema in Figure 2 to interpret –somewhat liberally – Edison's case, we can see that if we take a static picture at a moment when Edison and his associates were exploring different lines, we may see how their broad attention (resulting from a tonic LC mode) reflected an explorative behavior at the individual level and aggregated also at the organizational level. At other moments (as, for example, when narrowing down to one option among the many explored) the more focused attention (resulting from a phasic LC mode) showed exploitative behaviors.

Importantly for our argument, there is no evidence that Edison relied on different people to allocate exploration- or exploitation-oriented tasks, but that all the people involved in his labs tackled both types of challenges. Having individuals capable of shifting easily from exploitation to exploration and back also allows a group to do so: aggregated at the organizational level, the combination of explorative and exploitative behaviors is more likely to lead to an adaptive behavior that swiftly moves between the exploring-exploiting modes.

6. THE CHALLENGE OF MEASUREMENT AND EMPIRICAL VALIDATION

In applying neuroscientific findings and techniques to management problems, we need to be aware of some key epistemological differences between these research programs. Neuroscientists, and neuroeconomists for the large part, are interested in the average effects of their experimental manipulations in identifying the neural correlates of a given process (e.g., a utility evaluation) triggered by a homogeneous stimulus (e.g., increased levels of uncertainty) and producing a set of possible, observable, decisional outcomes (e.g., a type of decision in a game-theoretic scenario). Consequently, the pursuit of these types of research questions and the experimental designs generated tend to neglect individual variations around the mean response to the stimulus, and in fact consider them a nuisance (Frederick 2005), since the larger the variance the weaker are the mean-based results.

However, as Lubinsky and Humpreys (1997) note, a neglected aspect does not disappear because it is neglected, and there is no good reason for ignoring the individual variation around a mean response, especially if we have good logic to expect an important causal link between managerial decision-making and organizational performance, or, as in this paper, between the allocation of attention as an antecedent of decision-making behavior and its consequences in organizational behavior and performance. As neuroscientists do, we should care about what causes the average to work in a certain way, but our focus must be on the explanation of the differences: what might lead certain individuals and their organizations to display diverse reactions to similar stimuli, and consequently different levels of performance? This basic difference in epistemological approaches implies some challenges to management researchers who need to adjust some of the traditionally adopted neuroscience research methods in order to comply with their objectives.

A first challenge is that testing for differences requires a larger sample and implies higher costs in terms of time, laboratory access, and data processing. Also, the type of participants is different: many applications of neuroscience to economics, marketing, and finance use data from college students. However, if we want to understand differences in managerial decision-making behavior, it is necessary to sample managers, executives, and entrepreneurs of different kinds, with the aim of tracing differences in the neural correlates that antecede their behavior, and also to eventually be able to correlate the results on individual characteristics with those of the organizations or groups over which they exert significant influence. Differences in age and experience may shape the brain structure and the activations that can be observed. One interesting setting for testing our ideas would be among the entrepreneurs of small family enterprises. In those organizations, as described by Bodner and Vaughan (2009), the limited resources will possibly increase the impact on the organizational moves of what the entrepreneur attends to and the cognitive maps he does develop. Finally, replication is especially important in managerial studies since contextual effects related to task features, firm and sector characteristics, cultural traits and institutional conditions may alter the way individuals make decisions following the same set of stimuli, and the way organizations consequently perform.

Another distinctive feature of management scholarship requires researchers to go beyond uncovering what the effects of certain abilities might be, and to attempt to understand how these cognitive abilities can be developed and used successfully to improve organizational performance, so that abilities – say the flexibility to shift attentional mode as soon as unexpected uncertainty levels change – can be diffused to benefit organizational outcomes. One of the key principles of behavioral neuroscience, in fact, is that experience can modify brain structure long after brain development is complete. Brain plasticity refers precisely to the brain's ability to change structure and function. Experience is a major stimulant of brain plasticity and works by producing multiple, dissociable changes in the brain including increases in dendritic length, increases (or decreases) in spine density, synapse formation, increased glial activity and altered metabolic activity (Kolb and Whishaw, 1998). Research on humans produced the interesting result that “the plasticity of the nervous system remains throughout the life span and extends well into old age" (Taub, 2004). If the antecedents to certain managerial abilities are identified, it may imply that it might be possible to modify brain structure through different types of exercises and training, and thus gain abilities relevant to improving managerial functioning following different experiences and at different ages.

To design a study for testing the neuroscientific findings in a managerial setting it is necessary to create or adapt experimental tasks that cover a series of steps corresponding to the different constructs illustrated by the neuroscientific findings. An ideal option would be to obtain direct measures of the managers’ attention focus while facing different real-life decisions and to correlate such measures with the performance obtained out of those decisions (both at a purely individual level and at an organizational level) both in the short- and the long-term. However, given the difficulty (or impossibility) of measuring managers in the real context with the actual brain imaging tools, a good viable proxy would be to correlate the performance obtained, for example, in managerial decision-making simulations facing the exploration-exploitation dilemma with the precise attention focus measures obtained while completing different neuropsychological tasks in a lab context. There are different alternatives that researchers could follow to measure the ability of making decisions regarding exploring-exploiting, some of which are also compatible with brain imaging techniques that could allow researchers to measure not only performance in the exploration exploitation decisions (the observed behavior) but also the neural correlates of such decisions.

We now turn to discuss how each of the key constructs in this paper could be actually observed with the context of one specific task, which can be administered using fMRI techniques: the gambling task (Daw et al., 2006).

To understand the antecedents of the decision-making ability related to managing the exploration-exploitation dilemma, we have proposed four constructs based on the findings in neuroscience. The first construct is the level of uncertainty connected to a given decisional situation. The first step in the experimental design is thus to evaluate the manager's perception of the uncertainty of the outcomes in the task. This perception of uncertainty translates into a utility assessment, the second construct. Different parts of the brain intervene in utility assessment and, as we have shown, the ACC and OFC play important roles. Depending on the manager's assessment of utility in the current task, an attention mode arises, the third construct. As already explained, the LC plays a fundamental role in modulating the attention mode according to the perceived utility. As a consequence of the attention mode, the manager will then show a behavior, the fourth construct. In the case of broad attention (LC active in tonic mode), explorative behaviors arise and managers will act (or will propose solutions) in ways characterized by experimentation, flexibility, discovery and innovation. In the case of focused attention (LC active in phasic mode), exploitative behaviors will occur and managers will act selectively, according to refinement of current processes and efficiency in the current task. If the behavior matches what the situation demand (e.g. high uncertainty matched with explorative behavior and low uncertainty with exploitative behavior), higher performance can be expected.

Importantly, the ability to balance exploration-exploitation through flexible management of the situational requirements to achieve the appropriate attentional response can only be assessed if the decision process is replicated under stable contextual conditions. This adaptive process at the individual level can be linked, and the link empirically tested, to the organizational ability to balance the exploration-exploitation dilemma.

The four constructs we propose can be measured in an experimental context. These experiments involve two types of data. First, they require data derived from behavioral measurements during experimental tasks (e.g. response times, performance, etc.) and from questionnaires and interviews. Second, they require data on brain functioning, which can be obtained during experiments by using brain imaging techniques[2].

The particular technique to be used can be selected depending on the properties of brain-behavior association to be observed. If the study requires a high

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[2] The basic set of techniques used to generate neurological images is electroencephalography (EEG), magneto encephalography (MEG), positron emission tomography (PET) and fMRI. There are many limitations to the use of these techniques: they are expensive to operate and results are open to subjective interpretation. They are also intrusive for subjects although to different degrees. EEG and MEG are considered the least intrusive, while fMRI may cause many subjects discomfort related to having to lie still in a small space. Researchers must take the degree of intrusion into account since it affects data gathering, particularly if the subjects are busy managers and key decision-makers. Nevertheless, these techniques offer by far the best physical evidence to date on the activation of specific parts of the brain consequent to given stimuli.

spatial resolution, fMRI and PET will be required. If the study requires high temporal resolution, EEG or MEG would be suitable. A study that requires both high temporal and high spatial resolution could use a combination of these techniques (such as fMRI or PET with EEG/MEG).

Gambling in the magnetic resonance imaging machine

An experimental task that could assess the exploration-exploitation dilemma at the individual level and is compatible with the brain imaging techniques just exposed is the gambling task as adapted by Daw et al. (2006). In this experiment, participants play by choosing among four slot machines, to win as many points as possible. They are faced with the classical exploration-exploitation dilemma in a changing environment context. During the experiment different characteristics on the machines are manipulated (payoff average, uncertainty of returns, etc.) and participants must choose whether to continue to play on a particular machine or explore new possibilities in the hope of earning more points. While the individual is playing, her or his brain can be scanned (e.g. using fMRI) to obtain measures for each of the four constructs developed above. Of course, the task could be done in a normal PC and obtain only the behavioral performance measures of exploration-exploitation decision-making, depending on the strategies and payoffs obtained by the participant. Importantly, the software controlling the game allows a good level of manipulation of the uncertainty level. In addition, the utility perception and the attention mode can be measured using brain imaging techniques. Most management studies proxy for attention by time allocated to an activity (e.g. the famous study by

Mintzberg (1973), whose results were confirmed by Kurke and Aldrich (1983)). Other studies proxy for attention by the number of times a person refers to a certain issue (e.g. the number of sentences in a shareholder letter referring to a specific element (D'Aveni and MacMillan, 1990; Barr, Stimpert and Huff, 1992)). However, the ideas we propose do not require a measure for general attention; rather, we want to differentiate between two types of attention – broad and focused. The attention mode can be assessed by observing LC functioning using a brain imaging technique (for example, the participants can play the task while lying in the MRI scan) or by measuring pupil diameter, found to correlate remarkably well with LC tonic activity (Gilzenrat et al. 2003). The diameter of an individual's pupils changes under various conditions. For instance, the pupil diameter of someone who is thinking increases; the pupil of a tired person shrinks. These effects have been proven through a number of psychology (Shinoda and Kato 2006) and neuroscience experiments (Gilzenrat et al. 2003).

Finally, behavior can be observed based on individual choices. In this way, one task could be used to measure the decision-making performance when facing the exploration-exploitation tradeoff, and for manipulating and measuring the different constructs that we have illustrated and that affect such performance (uncertainty, perceived utility, attention focus). Table 2 summarizes how each construct can be defined and measured in an experiment such as the gambling task.

[INSERT TABLE 2 ABOUT HERE]

This gambling task could be complemented with other alternatives, such as simulation, decision-making vignettes and self-reported scales, to have a more reliable measure. A treatment of all the available alternatives using these techniques is out of the scope of this article, but the authors will be pleased to provide a synopsis and an assessment of results from ongoing empirical work to all interested scholars.

For the purpose of testing the ideas proposed in this manuscript[3], the first best option is certainly to correlate the direct measures of the managers' attention focus in different real-life situations with the performance obtained in the real decisions (both at a purely individual level and at an organizational level) both in short- and long-term. However, given the difficulty (or impossibility) of measuring managers in real situations with the actual brain imaging tools, a good viable proxy would be to correlate attention focus measures obtained while performing different neuropsychological tasks in a lab context, with for example, managerial decision-making simulations facing the exploration-exploitation dilemma. The performance measures obtained in these simulations can be compared with the measures obtained in self-reported scales such as the cognitive flexibility scale (Martin and Rubin 1995) or the recent scale of exploration-exploitation activities by Mom, Van Den Bosch and Volberda (2009).

7 CONCLUSIONS

This paper addresses a dilemma common to organizations. Managing the trade-off between exploitation and exploration is fundamental to adaptive behavior and

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[3] While at the time of writing the study was still in its infancy, at the time of publishing the ideas were implemented along lines consistent with those here discussed and very promising preliminary results started to be obtained.

learning in increasingly complex and rapidly changing contexts. Although there has been much research on this trade-off, there are still several key gaps in the literature. First, we still know little about "how" exploration and exploitation are actually done. Second, the appropriate level of analysis at which the exploration-exploitation tradeoff is solved is not clear. Third, in many cases what is meant by exploration-exploitation is not very clear. Fourth, variation among individuals in the tendency to respond in an exploitative or explorative way to a given stimulus, and on the ability to shift their responses according to changes in the environmental conditions, have not been explored. To start addressing these key analytical gaps, we thus propose a framework and a method which, in our view, contributes particularly to the micro-level problem of individual-level variance in behavior. We provide a definition that is compatible with the management and the neuroscientific literature that we are using. We focus on the individual as the fundamental unit of analysis and study how exploration and exploitation are done at the micro, neurological level in terms of the processes going on in an individual's mind and the ensuing behavior when faced with a given environmental stimulus. Why does this framework matter? We believe there are at least four possible areas of contribution for the ideas put forward in this paper.

7.1. "How" the tradeoff is solved – a micro perspective

As discussed earlier in this paper, there is still a remarkable lack of clarity as to what is the appropriate level of analysis for understanding the trade-off between exploitation and exploration. At the organizational level, many have focused on the attributes that make organizations more or less explorative (e.g. Tushman and

O'Reilly, 1996). Others have argued instead (e.g. Papo, 2007) that individual-level processes ought to play a more central role in understanding the origin of new ideas. Obviously, these issues are related. Yet, we still know very little about how micro-level processes build up to organizational outcomes. We used the example of Menlo Park's activities to argue that the crucial issue here is not that of allocating exploitative vs. explorative tasks to those individuals or organizations which are best suited to that task. Rather, our framework points to the idea that what matters to balance the tradeoff is not specialization, but the ability of key decision-makers to shift seamlessly from one task to the other, as we illustrated with the process Edison enacted in one of his key innovations. At the organizational level, this argument is consistent with recent research on the dynamics of innovation in complex technical systems, which has warned against the dangers of strategic outsourcing, often grounded in the belief that exploitation and exploration are actually separate activities which can be attributed to different types of organizations (e.g.(Brusoni et al. 2001)). While there is some evidence of the dangers of outsourcing stemming from excessive specialization, micro-founded explanations are in short supply. The application of neuroscience to managerial decision-making offers important opportunities for this line of inquiry to be developed to include the study of interactions among individuals engaged in these high-level cognitive tasks, and the generation of collective results that go beyond the sum of individuals' capacities. While the "aggregation" of individual capacities and behaviors into organizational ones remains a main limitation from the neuroeconomics field (Papo 2007), this paper attempts, at least, to identify similarities between micro- and organization-level processes which ought to be further explored to generate sensible micro-foundations of macro-behaviors.

7.2. “How” the tradeoff is solved – a macro perspective

Domains that have traditionally focused on macro-organizational analyses such as organization theory, strategy and entrepreneurship might benefit from the development of a theory of exploration and exploitation based on the neurological processes occurring within individual managers’ brains.

For example, consider one of the basic insights in March’s (1991) seminal article, which is related to the fact that exploration requires heterogeneity in human capital, which disappears without constant personnel turnover because the newcomers learn the code and adapt to the firm’s modus operandi. March concludes (somewhat paradoxically) that the slower the learning of the code, the higher the exploration in the firm. However, the analysis in this paper points to an alternative mechanism which does not rely on personnel turnover to balance the exploration-exploitation dilemma, but rather focuses on the organizational members’ neurological characteristics, i.e. their propensity to function in tonic or phasic mode in the neuro-modulation of their attention. It could be speculated that a broad attention span caused by the tonic activity of LC leads to a relatively slower socialization process (i.e. learning of the code) and thus more exploration at organizational level.

For scholars engaged in the study of entrepreneurship, our work offers the possibility to theorize and empirically validate (with objective measures) insights related to the explanation of explorative decisions, which might generate the foundation of new ventures internal to the firm (entrepreneurship) or outside it (spin-offs or start-ups). The launch of a novel enterprise can be viewed as the consequence of the continuous allocation of attention to explorative processes, and the development of neurological foundations for such choices can be particularly useful to this field. For similar reasons, strategy scholars might be able to build on a better understanding of the neurological foundations of exploration-exploitation decisions to develop models of strategic choice based on the idiosyncratic characteristics of the strategy-makers, over and above the influence of the industry context and the organizational endowment.

7.3. Enhancing attention modulation

Third, and more practically, the framework we propose in this paper might be used to develop teaching tools to foster individuals' ability to control and properly shift the focus of their attention. There is an element of plasticity in the neurological processes we discuss here, which can be leveraged to develop training programs to improve individuals' responses to changing environmental circumstances. Since attention modulation affects the ability to properly make decisions regarding exploration-exploitation, it will be then possible to adapt some instruments which have been developed for improving the attentional control (Sohlberg and Mateer 1989, 2001). Very interestingly, for example, the analysis of the modulation of attention and its impact on decision-making might open new venues in managerial and entrepreneurial education through the development of tools and techniques which management students and practitioners can use to enhance their attentional control. These tools and techniques can be very varied, ranging from traditional in-class methods (for example, for acquiring awareness of perceptive biases) to mental control practices (as, for example, neuroimaging studies have demonstrated the positive impact of meditative practices on the improvement of functional up-regulation of brain regions affecting attention control. For a recent review see Rubia – in press). In addition, since many psychiatric disorders of higher level cognition are thought to be due to deficits of attention (Posner and Petersen 1990) researchers could adjust the tools used to treat patients of attention disorders to be applied to managers aiming to improve their attention control.

7.4. Reflection and some convergence among different domains

On a broader note, a fourth contribution aims at reaching out to the now-broad crowd in social sciences interested in exploring the neuro-scientific foundations of economic and organizational behavior. Social sciences are highly segmented in different knowledge domains. The findings of our work might foster a more integrated discussion. For example, mainstream economists might consider it interesting to move beyond the replication of results based on game theory, the focus of most neuroeconomics work so far, to develop novel insights into the neurological foundations of economic behavior. Also, the shift towards the explanation of variance across individual traits and consequent behavior, as opposed to the characterization of the mean tendency for the population of decision-makers, might serve to correct a standard bias in the discipline.

On the other side of the discipline’s fence, evolutionary economists will appreciate our attempt to develop some of the micro-foundations of the work related to how firms learn and evolve. The appropriate balancing of explorative and exploitative search is arguably a cornerstone of their theories. Depending on the attention mode, a certain way to decompose the problem will emerge and the search space will be defined accordingly. Search, therefore, is a consequence of the attention mode. If the attention focus is broad, for example, problems will be decomposed in broader modules, while a narrow attention focus will result in problems being decomposed in finer modules. Brusoni, Marengo, Prencipe and Valente (2007) show that the balance to this trade-off depends upon the volatility of the problem environment. In stationary environments there is an evolutionary advantage to over-modularization, while in highly volatile environments, contrary to the received wisdom, modular search is inefficient in the long run. Similarly, we propose that in low-uncertainty tasks exploitative behavior (i.e. deriving from a narrow attention mode and involving high decomposition of problems) would be advantageous, while the opposite will be true in the case of highly uncertain tasks: high decomposition is not efficient and explorative behavior derived from broad search will lead to better performance.

The organizational behavior field, with its orientation towards studying individual behavior in firms, is the obvious audience for the ideas discussed here. The main value for scholars in this field is that our findings expand their research agenda, which traditionally has been built on the application of social and cognitive psychology, to include the novel insights and methodologies developed in the neurosciences which are applicable to the study of organizational behavior phenomena. While neurologically founded findings might in the end confirm what many have already argued on the strength of socio-metric surveys and psychological tests, neurosciences might contribute by offering better theoretical foundations to understand exactly why individuals behave in a certain way when isolated, and how organizational life is impacted by their responses.

Also, neuroscientists might find of interest the application of recent findings about the modulation of attention to the explanation of economic behavior and performance. The empirical validation of conceptual advancement in different decision-making settings and the search for differences among healthy subjects engaged in real-life, high-level decisions might offer good opportunities for the development of further understanding of the neural correlates of some of the highest functions of the human brain: the ability to search for novel approaches to the solution of unstructured problems in natural settings.

7.5 Future research

Of course, many other things might impact individuals' ability to shift their focus of attention. The framework we have discussed here emphasizes the cognitive, rational elements of response to stimuli at a given point in time. Future research might explore other ways to approach the exploration-exploitation dilemma. For example, the balance between exploration and exploitation seems to be sensitive to time horizons, and humans show a greater tendency to explore when there is more time left for a task, presumably because it allows sufficient time to enjoy the fruits of those explorations (Carstensen et al. 1999). Besides, individuals' impulsivity or differences in perception of time influence decision-making (Wittmann and Paulus 2009), and so it would be useful to take the dimension of time into account as the exploration-exploitation dilemma encompasses the anticipation of future rewards. It would also be interesting to explore how emotions affect the management of the exploration-exploitation dilemma, since subjects whose brain activity displays good cooperation between the limbic area of the brain (emotional area) and the prefrontal cortex (thinking area) are the most successful in games based on experimentation (Bhatt and Camerer 2005). Finally, future work could examine the tendency towards exploiting rather than balancing exploring-exploiting from an impatient behavior point of view, using the findings on the neural correlates of time discounting (McClure et al. 2004). As well as empirically testing the model proposed here, these ideas would provide a more complete understanding of the exploration-exploitation dilemma at the micro level.

To conclude, it should be noted that the data on brain functionality and the use of neuro-imaging techniques have only begun to demonstrate their utility in complementing existing data sources, deepening the microfoundations of managerial behavior and developing better tools for improving cognitive abilities. The combination of novel empirical techniques and the objective strength of neuroscientific evidence, free from typical limitations of subjective data collection processes, to ground the theories of managerial behavior, demand increasing attention from management scholars. This becomes even more important if we include the potential to contribute to the ultimate goal of social science – as proposed by Glimcher and Rustichini (2004): the development of a unified theory of human behavior, without which the advancement of our understanding of managerial behavior cannot progress.

8. Figures and Tables:

Fig. 1: LC, OFC and ACC location in the brain

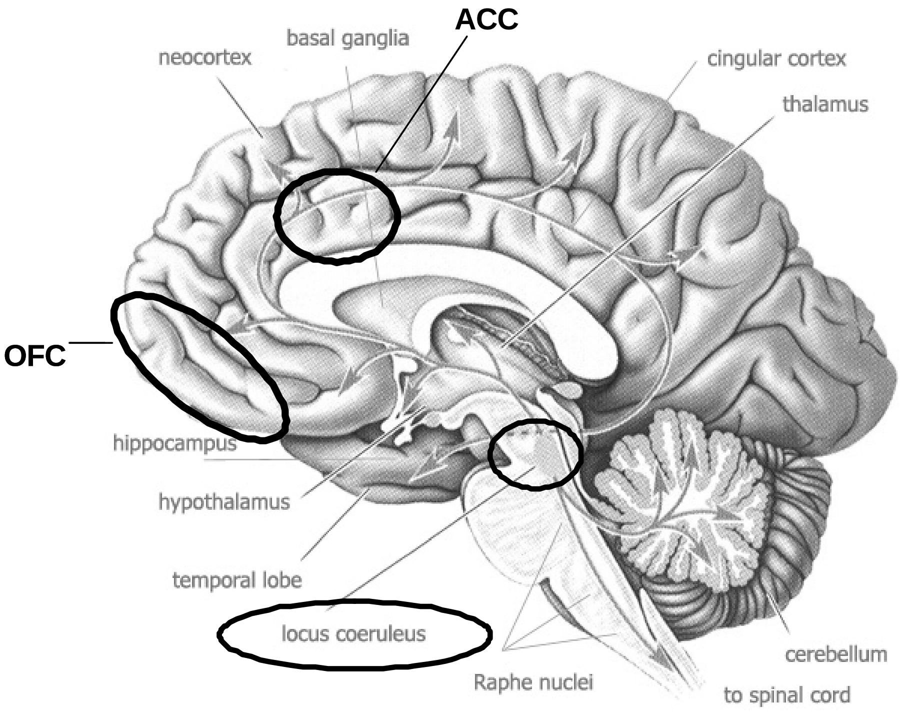


Fig. 2: Key decision-makers’ attention and organizational behavior

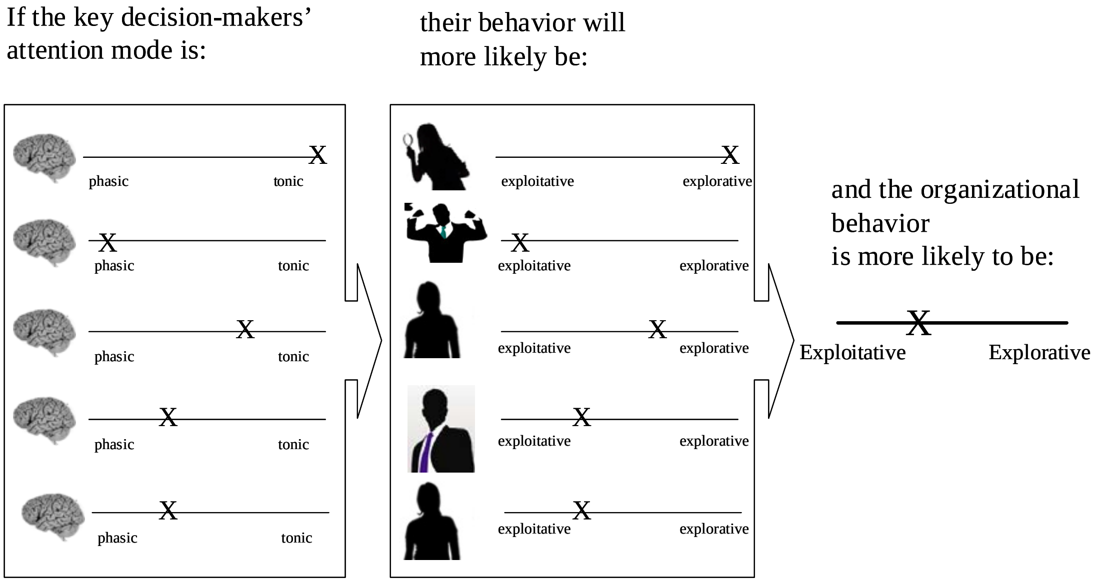
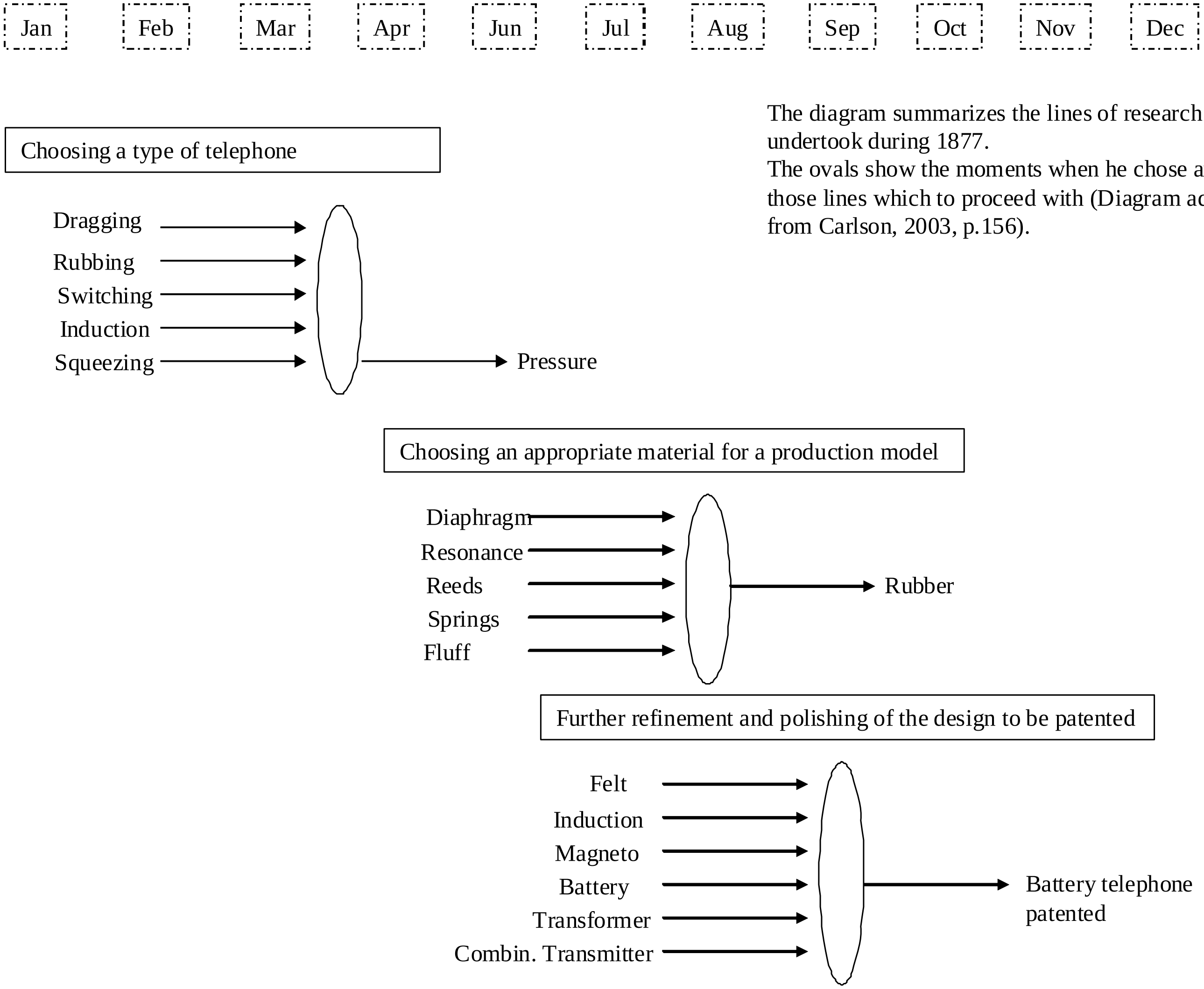


Fig. 3: Edison’s lines of research for developing the telephone



The diagram summarizes the lines of research Edison undertook during 1877.
The ovals show the moments when he chose among those lines which to proceed with (Diagram adapted from Carlson, 2003, p.156).

Fig. 4: Example: Edison and the telephone invention

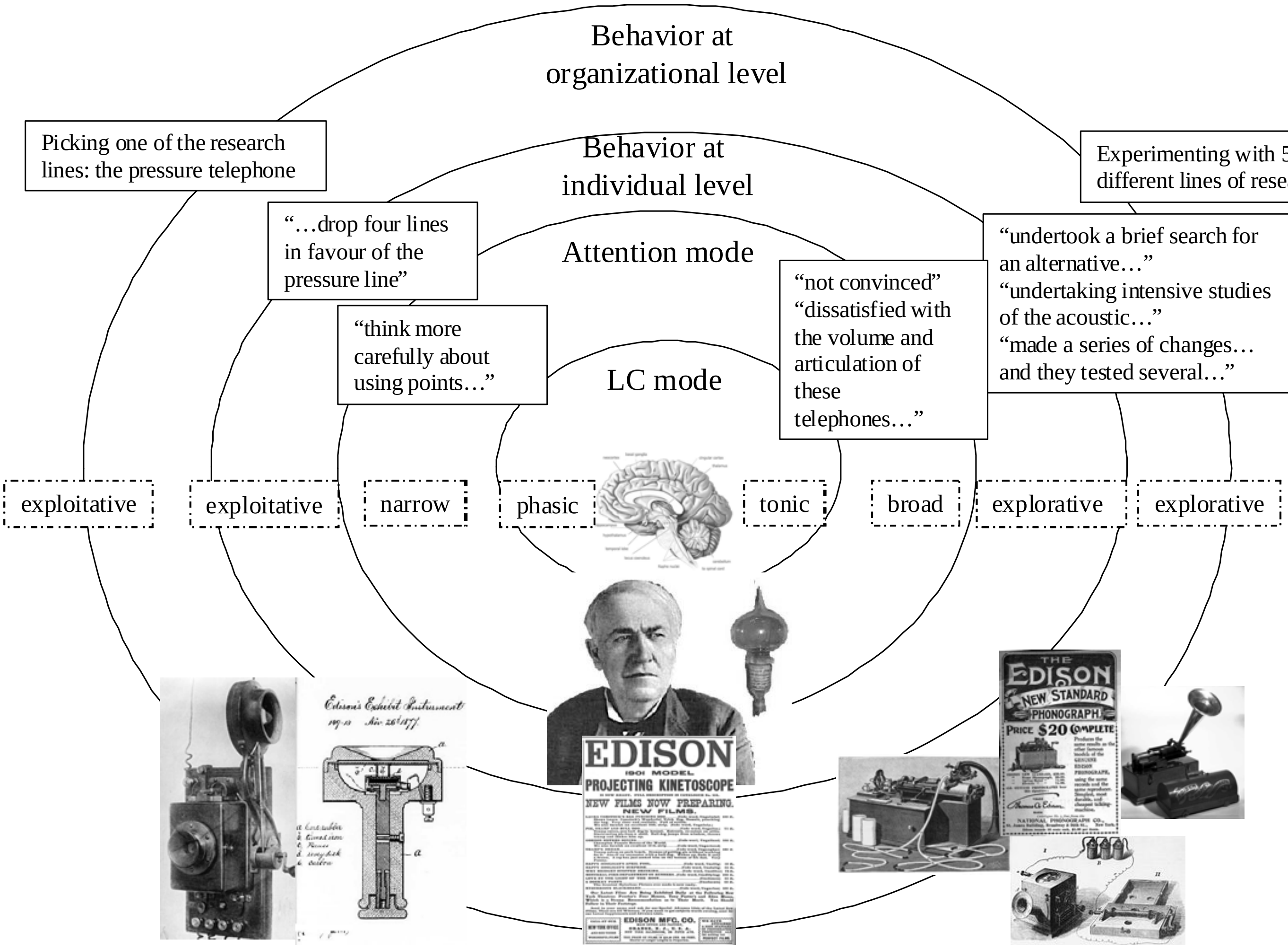


Table 1: Definitions of Exploration and Exploitation

Quotes from:	Exploration	Exploitation
March ,1991	Exploration includes elements captured by terms such as search, variation, risk-taking, experimentation, play, flexibility, discovery, innovation. The essence of exploration is experimentation with new alternatives. Its returns are uncertain, distant, and often negative.	Exploitation includes such things as refinement, choice, production, efficiency, selection, implementation, execution. The essence of exploitation is the refinement and extension of existing competences, technologies and paradigms. Its returns are positive, proximate and predictable.
March, 2006	Pursuit of what might come to be known.	The refinement and implementation of what is known
Holmqvist, 2004	Exploration is concerned with creating variety in experience, and thrives on experimentation and free association Variety in experience through search, discovery, novelty, innovation and experimentation.	Exploitation is about creating reliability in experience, and thrives on productivity and refinement. Creates reliability in experience through refinement, routinization, production, and implementation of knowledge.
Levinthal and Rerup, 2006	"Experimenting with a novel action implies forgoing the use of existing, established practices. In this sense, mindfulness corresponds to exploratory behavior…"	"…and less-mindful behavior is akin to exploitative behavior."
Zollo and Winter, 2002	Exploration activities are primarily carried out through cognitive efforts aimed at generating the necessary range of new intuitions and ideas (variation) as well as selecting the most appropriate ones through evaluation and legitimization processes.	By contrast, exploitation activities rely more on behavioral mechanisms encompassing the replication of the new approaches in diverse context and their absorption into the existing sets of routines for the execution of that particular task.
Smith and Tushman, 2005	Exploration is rooted in variance-increasing activities, learning by doing, and trial and error, exploration creates futures that may be quite different than the organization's past.	Exploitation is rooted in variance-decreasing activities and disciplined problem-solving exploitation builds on an organization's past
Levinthal and March, 1993	"the pursuit of new knowledge of things that might come to be known".	"the use and development of things already known".

Table 2: Example of how constructs could be defined and measured in a multi-armed gambling task

Construct	Defined as:	Possible measure
Situation Uncertainty	It can be defined in terms of: 1.Frequency (# times task is repeated during x time) 2.Heterogeneity (degree of novelty) 3.Causal ambiguity (number and degree of interdependence of subtasks; degree of simultaneity among subtasks) (Zollo and Winter, 2002)	Payoffs change randomly from trial to trial (manipulation of diff. situation characteristics)
Perceived utility	How much the individual likes the possible outcomes of the present situation (taking into account the anticipation of current outcomes and the memory of past decisions) (Aston-Jones and Cohen, 2005) (high –low on a scale depending on method)	ACC and OFC functioning using fMRI
Attention mode	What type of attention is devoted to a situation: broad or narrow (Aston-Jones and Cohen, 2005)	LC operation mode using fMRI Or proxy with pupil diameter
Behavior	How much search for new alternatives is done (high being exploration, low exploitation) (Aston-Jones and Cohen 2005)	The observed strategy followed by the individual (i.e. her/his choice in each trial)

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Cognitive Control Capabilities, Routinization and Decision-Making Performance

Daniella Laureiro-Martínez

CURRENTLY UNDER REVIEW

Abstract

This paper studies both the cognitive and the behavioral foundations of decision-making at the individual level of analysis. It uses a study conducted with 89 graduate students and a model that combines highly mindful cognitive processes and routinized (less-mindful) behavioral responses to explain the performance of R&D resource-allocation choices. Three findings emerge from the data. First, cognitive control capabilities, i.e. the supervisory cognitive mechanisms through which individuals monitor and control their own attention processes, positively influence decision-making performance. Second, the degree of routinization of decision-making also has a positive influence on performance. Third, routinization fully mediates the impact of cognitive control capabilities on decision-making performance. Hence, both high and low levels of mindfulness are essential to maximize the performance of strategic decisions such as R&D resource allocation. Counterintuitively, however, higher cognitive control capabilities are connected to higher levels of routinization, which in turn enhance performance. Also, combinations of high routinization/low cognitive control capabilities perform significantly better than their complements, giving routinization a more important role than cognitive control capabilities in explaining decision-making performance. These findings might contribute towards the development of an integrated theory of cognition, decision-making and learning.

Key words: microfoundations; routines; routinization; cognition; cognitive control capabilities; decision-making; strategy.

1. Introduction

In recent years, several calls for the development of a richer characterization of managerial decision-making, integrating both mindful and “less-mindful” perspectives, have been made by scholars in strategy and organization (Argote 2006; Gavetti et al. 2007; Levinthal and Rerup 2006a; Lubatkin et al. 2006; Weick and Sutcliffe 2006). Important attempts to connect and study the role of learning and decision-making processes at different levels of intentionality and mindfulness have also been made (Narduzzo et al. 2000; Salvato 2009; Salvato and Rerup forthcoming; Tripsas and Gavetti 2003; Zollo and Winter 2002). In particular, Levinthal and Rerup (2006) have argued that, at the performative level, mindful processes are underpinned by key elements of less-mindful ones, which provides a first way to view the interdependence between them. At the same time, scholars in cognitive neurosciences are making headway in understanding how more- and less-mindful processes interact at the neurological level (Bechara and Damasio 2005; Cohen 2005), which I suggest needs to be taken into account to progress in our understanding of managerial decision-making and learning processes.

In the effort to bridge research in strategy and organization with recent developments in cognitive neurosciences, this paper proposes a microfounded explanation of how mindful and less-mindful processes interact when individuals make strategic decisions. Although mindfulness is a nuanced concept, for our present purposes, I define a ‘mindful process’ as ‘one carried out with full awareness and volition’ and a ‘less-mindful process’ as ‘one requiring little attention, intention or thought’.

This paper intends to contribute to the mindfulness debate in several ways. First, on the strength of recent research in cognitive psychology and neurosciences, I introduce the concept of Cognitive Control Capabilities (CCCs) to precisely define, and empirically observe, the mindful side of decision-making. Second, I study two possible ways in which less mindful processes, embodied in routine-like processes, might interact with mindful processes to influence performance. One way views routinization as a moderating factor, enhancing the effectiveness of cognitive processes, roughly in line with some of the theoretical arguments in the extant literature (Rerup and Levinthal, 2006; Weick and Sutcliffe, 2006). An alternative way views mindful processes influencing the degree of routinization, which in turn positively affects performance. This view is consistent with intuitions by some of the early thinkers of modern psychology (Dewey 1922; Whitehead 1911); as well as with the most recent advancements in neuroscience on the pervasive role of neuroplasticity (Kolb and Whishaw 1998; Schwartz and Begley 2002). Third, I empirically test a framework in which both “mindful” and “less-mindful” elements interact to explain decision-making performance.

My argument proceeds as follows. First, I discuss the two analytical building blocks -mindful processes (i.e. CCCs) and less-mindful processes (i.e. routinization)- and propose hypotheses regarding the relationship between them and decision-making performance. Second, I propose a multi-method approach for measuring cognitive control capabilities, routinization and decision-making performance. The method combines a strategic decision-making simulation, neuropsychological tests and a qualitative technique to assess the degree of routinization of decision procedures. Finally, I present my main results and discuss their implications for both theory and practice.

2. The two sides of the coin: mindful and less-mindful processes in strategic decisions

Many calls have asked for a richer characterization of strategic decision-making (Argote 2006; Eisenhardt et al. 2010; Gavetti et al. 2007; Levinthal and Rerup 2006a; Lubatkin et al. 2006; Weick and Sutcliffe 2006). Strategic decisions have been defined as “important, in terms of the actions taken, the resources committed, or the precedents set” ((Mintzberg et al. 1976)p.246). Besides, strategic decisions are genuine and make a difference. “They are genuine in the sense they are neither random nor predetermined. […] They make a difference in the sense that today’s choice permanently affects future states of the world.” ((Loasby 1976) p.5). On this ground, I now introduce the mindful processes (i.e. CCCs) and less-mindful processes (i.e. routinization)- as antecedents of strategic decision-making and propose hypotheses regarding the relationship between them and decision-making performance.

2.1 Less-mindful processes: Routinization

Routines are the cornerstones of the behavioral and evolutionary views of the firm (March and Simon 1958; Nelson and Winter 1982). I use the label ‘routines’ to indicate recurring action patterns that act as standard solutions and are enacted in response to a signal that captures a state of the environment. A great deal of organizational activity follows recurring, stable and relatively reliable patterns of action (Nelson and Winter 1982). All individuals' activities are strongly regulated by routines (Forgas 1983) and when taking decisions we grossly simplify complex problems applying and adapting routines (Loasby 1976). Routinization is defined as the ability to develop and enact a behavioral repertoire which provides standard solutions (routines) for choice problems (Betsch and Haberstroh 2005; Betsch et al. 2001).

The constant use and adaptation of routines permeates decision-making to the extent that what appear as new decisions can be seen as recombination and adaptation of old routines, or as Loasby put it 'decision making becomes decision adapting' (Loasby 1976). During the past decade, decision-making researchers became increasingly interested in the effects of routinization on decision-making and its subsequent performance (Beach and Potter 1992; Betsch et al. 2004).

In Nelson and Winter's (1982) original synthesis, the concept of routine was not separable from mindful processes of decision-making. Routines were specifically pinpointed as the focusing device necessary to spot exceptions in normal performance on which to focus the search for novel solutions. Crucially, routines were linked to firms' ability to introduce innovation through processes of recombination, replication, imitation and mutation. However, many reinterpretations changed this emphasis, weakening the relationship between routinization and decision-making by highlighting the mindless element of routine-based behavior; contributions from applied psychology also expanded on the theme (Langer 1989; Weiss and Ilgen 1985). Both negative and positive effects of routinization have been identified.

Regarding negative effects, the main argument is that routinization tends to lead to inertia as routines become taken-for-granted notions of ‘the way we do things around here’ and thus reduce awareness of the need or capacity for change. Over time, reliance on standardized action patterns is accompanied by reduced cognitive activity and attention is focused only on a few given, salient features. Whereas this minimal cognitive processing may sometimes liberate attention for other purposes, in other cases the decision-maker may perceive novel situations as normal in terms of those few salient features, and will fail to realize that change is necessary because of changing environmental circumstances (Langer 1989; Weiss and Ilgen 1985). However, recent and ongoing research in both social and cognitive neurosciences tends to argue that such negative effects are the outcome of rather specific circumstances and that routinization might actually be a necessary condition for change and adaptation, rather than a hindrance.

Regarding positive effects, advocates of routinization argue that it acts as a major source of learning and organizational competence. An important feature of routines is that they encode the knowledge of past solutions and thus reduce the need for deliberative efforts, freeing up scarce cognitive resources to focus on complex problems (Levinthal and Rerup 2006a). As Cohen et al. (1996) note, ‘routinized behaviors should […] be based on the absence or the reduction of active thinking’. (p. 695). Also, routinization fosters faster decision-making which, in turn, allows decision-makers to keep pace with changes in the environment and thus achieve superior adaptation and, eventually, better performance in rapidly changing environments (Eisenhardt 1989).

Several authors have been careful to avoid the image of routines as rigid, immutable patterns. These authors have emphasized the flexible aspects of routines which, through individuals’ enactment and reinforcement, can lead to change and adaptation (Feldman 2000; Pentland and Rueter 1994). More specifically, on the strength of recent research, I argue that agency is inextricably present in routine-based behavior because individuals are typically free to choose which routines to adopt and, crucially, how to implement them (Feldman 2000; Feldman and Pentland 2003; Rerup and Feldman 2010). Moreover, through routinization, decision-makers stabilize their expectations and perceptions of the environment. This might lead to suboptimality circumstances (Cohen and Bacdayan 1994), but most of the time routinization advantages in terms of encoding past solutions and saving cognitive resources and time will outweigh its disadvantages, leading to better decision-making performance. I therefore propose[4]:

Hypothesis 1: The higher the level of routinization of individual decision-making, the better the decision-making performance.

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[4] Given that literature has also argued for a negative relationship between routinization and innovation performance, we also developed and tested an inverted-U relationship between the the level of routinization of individual decision-making and the innovation performance. The analyses did not led to any significant results. For the sake of brevity we do not present those analyses in this document here.

2.2 The mindful processes: Cognitive Control Capabilities

While routinization may be necessary to find solutions and make decisions, it does not explain *per se* firms' or individuals' differential abilities in finding such solutions and making decisions. To analyze this problem, I need to introduce a second building block, related to the mindful side of the debate. I build upon the neuropsychological literature on the supervisory cognitive mechanisms that deal with the control of attention. Attention control mechanisms are used when we perform such activities as purposefully paying attention, planning, organizing, forecasting, strategizing, abstracting and drawing analogies. They also enable us to carry out goal-directed behavior and to reflect and inhibit inappropriate actions (van den Boss 2007, Norman and Shallice 1986, Shallice 1994). In this paper, I term these functions Cognitive Control Capabilities (CCCs) and define them as 'the supervisory cognitive mechanisms through which individuals monitor and control their own attention and cognitive processes'[5].

Over the last decade, CCCs have come to be fully appreciated by psychologists and neuroscientists (e.g. (Goldberg 2001; 2009)) because of their impact on decision-making. By controlling and managing other cognitive processes, CCCs govern activities such as rule acquisition,, abstract thinking, planning, initiation of appropriate actions and inhibition of inappropriate ones, and selection of relevant information (Loring 1999). The work of influential researchers in the field of cognitive

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[5] The cognitive control capabilities have been referred using different names as "executive functions", "executive system", "supervisory attentional system", or "cognitive control". In order to prevent confusion with the management literature in the use of the term "executive" I adopt the term cognitive control, first introduced by the influential psychologist Michael Posner in 1975 and call these functions 'cognitive control capabilities'.

control (Michael Posner, Joaquin Fuster, Tim Shallice among others in the 1980s and Trevor Robbins, Bob Knight, Don Stuss more recently) has laid much of the groundwork for CCCs. Different models have been developed in an effort to measure the CCCs. These models have been considerably refined lately thanks to brain imaging techniques (Knudsen 2007). Depending on the specific aim of the model, whether it is clinical or for research, a different function of the CCCs is emphasized. The most cited models in this literature coincide in including four functional components –the names change slightly according to the approach- that capture the main purposes of the CCCs: attention control, working memory, planning and generativity and reflective capacity (Barkley 2001; Barkley et al. 2007; Desimone and Duncan 1995; Knudsen 2007; Miller and Cohen 2001; Sohlberg and Mateer 2001). These four components are not perfectly separable from each other. However, each of them embodies a main distinctive function. Attention control reflects the ability to focus on relevant information and maintain attention on such selected information while avoiding distractors. Working memory is the ability to hold multiple pieces of information uppermost in the mind and being able to process them. Planning and generativity refers to the ability to make causal relations, generate alternatives, and anticipate the consequences of plans. Reflective capacity refers to the ability to reflect and to resist reporting the first answer that comes to mind, to inhibit inappropriate actions and sometimes to engage in abstract thinking to determine the appropriate action.

All these functions are intimately related to our abilities to learn, search and make decisions. More specifically, CCCs allow people to be cognitively flexible, adapt their cognitive and behavioral patterns to context. They serve to shift the control of behavior from the immediate context and the temporal *present* to broader representations and hypothetical futures useful to winnow out novel alternatives (Barkley 2001).

However, CCCs are limited, do not determine behavior, nor do they guarantee success in our decision-making efforts (Desimone and Duncan 1995). The number of stimuli we can attend to is limited, so cognition is bounded (Kahneman 1973; Pashler 1998; Robinson-Riegler and Robinson-Riegler 2004). The existence of such limits has been confirmed by psychological evidence focused on the depletion of cognitive resources (Baumeister et al. 1998; Muraven et al. 1998). Still, CCCs are essential for taking proper decisions and succeeding in real-life situations.

CCCs are particularly important in innovative contexts, when the environment changes and routinized responses do not suffice (Helfat and Peteraf 2009 ; Norman and Shallice 2000). Since the environment can be unpredictable, CCCs are vital in paying attention to the varying signals it generates, recognizing novel or unexpected situations, and taking proper decisions when unusual events arise. They allow decision-makers evaluate a situation, self-monitor their decisions and lead their organizations to respond to the changes in the environment by adapting their cognitive and behavioral patterns to the context. I therefore hypothesize that:

Hypothesis 2: The stronger the decision-maker’s cognitive control capabilities (CCCs), the better the decision-making performance.

2.3 Bridging the mindful and the less-mindful

> “habit diminishes the conscious attention with which our acts are performed. . . . the more of the details of our daily life we can hand over to the effortless custody of automatism, the more our higher powers of mind will be set free for their own proper work.” William James [1899: 114]

Mindful CCCs are bounded by their reliance on scarce cognitive resources (Desimone and Duncan 1995; Duncan et al. 1996). By economizing on cognitive resources, less-mindful routines are the backbone that allows individuals’ mindful processes to take place when necessary, and to impact performance (Levinthal and Rerup 2006a).

Just as we have developed labor-saving devices to free us from chores that do not require our attention, so routines free our limited cognitive resources from tasks in which they are no longer needed. In this way, we can shift our attention, time, and energy to those tasks that require them (Bargh and Chartrand 1999; Kahneman 1973; Posner and Snyder 1975). For this reason I argue that routinizing, as well as having a direct effect on decision-making (see Hypothesis 1), also allows CCCs to flourish by focusing scarce cognitive resources on the exceptions that require attention. In the absence of routinization, CCCs would dissipate, since attention would be dispersed across too many mundane and repetitive tasks, preventing them from being used, for example, to interpret potentially novel signals coming from the environment. In the presence of routinization, cognitive resources are economized, CCCs can fully leverage on them, and superior decision-making performance can be achieved. The third hypothesis therefore argues for a moderating effect of routinization on the link between CCCs and decision-making performance, and reads as follows:

> Hypothesis 3: The higher the level of routinization of individual decision-making, the stronger the effect of CCCs on decision-making performance.

However, there might be another, hitherto unexplored link between the two factors. CCCs might allow decision-makers to develop cognitive frames about the problem at hand and design appropriate strategic responses in the form of patterns of actions, or 'what to do when X happens'. In other words, CCCs might be an antecedent of routinization. How can CCCs explain the emergence and the adaptation of routines? As stated, CCCs deal with the control of attention, which governs the narrowing of the number of issues that are focused on and the sustaining of attention on selected information (Posner and Petersen 1990). Also, CCCs are involved in abstract thinking and in developing representations and plans for hypothetical futures, keeping different pieces of information in mind, integrating seemingly disconnected issues and establishing cause-and-effect relationships (Cohen et al. 2004; Posner and Petersen 1990). So it may be that superior CCCs will enable decision-makers to create and adapt routines to deal with the complexities of their environments. In turn, and as per Hypothesis 1, routinization will enhance decision-making performance. Therefore, another possible role of routinization is one of (partial or full) mediation between CCCs and decision-making performance: higher cognitive capacity will produce routinized behavior more quickly, which might in turn enhance decision-making performance. Therefore I propose:

> Hypothesis 4: The level of routinization mediates the impact that cognitive control capabilities (CCCs) have on decision-making performance.

Figure 1 summarizes the hypotheses. I intend to explain performance in decision-making as a function of the interplay between CCCs and routinization. In the following, I explain how I operationalized these concepts and strategic decision-making through neuropsychological tasks and a simulation.

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Insert Figure 1 about here

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3. Method

3.1 Participants and Design

I designed an observational study, i.e. a natural experiment design. In contrast with controlled experiments, in this design participants were not previously assigned to treated groups. Instead, I aimed at capturing natural differences in decision-making performance. I did not use manipulations but obtained laboratory measures of individuals' decision-making performance, propensity to routinize and several of their cognitive capabilities. I refined the study design in two pilot sessions with 10 participants each. They underwent all the same screening and compensation conditions as the actual participants, but were not included in the study; nor did they have any contact with the actual participants. Prior to the study, all potential participants followed a rigorous screening procedure to comply with the guidelines of neuropsychological studies. According to their results, participants were assigned to two of four sessions (see Appendix 7.1). All participants gave their written informed consent to take part in the study.

Eighty-nine graduate students of management and economics of innovation (44 women and 45 men) volunteered to participate in two sessions (total time about 5.5 hours) for monetary compensation (mean €60, or approximately $72). Their mean age was 24 (SD = 2.289).

At the beginning of each session, participants were randomly assigned to a computer in the laboratory. General instructions were provided in oral and written form. In addition, specific on-screen instructions, including examples, were provided before the participant began each task. In the case of more complex tasks (such as the n-back) all participants played trial sessions before the session that was actually used to gauge their performance. If needed, further explanation was provided by the researcher. Including the breaks, the first session lasted for about 2.5 hours and the second session for three hours. During the breaks beverages and snacks were provided.

During the first session, participants completed a strategic decision-making task. They had 2.5 hours to read a case describing an organizational situation and then play the decision-making simulation. Consistent with the pilot results, all participants finished before the time was over. Following a 15-minute break (with refreshments) participants answered a personality questionnaire (Cloninger 1994) and were debriefed.

During the second session, participants completed a routinization task consisting of four runs of 10 minutes each, separated by one-minute breaks. After the fourth run, participants answered one open question regarding the strategy they followed while playing. A compulsory 15-minute break followed the debriefing. Refreshments were offered. After the break, participants completed several cognitive tasks, described below under the title ‘CCCs tasks’. The tasks were automatically set by a computer program and presented in randomized order, separated by one-minute breaks. Unlimited time was given to read instructions, offering additional opportunities to rest when needed. After the CCCs tasks were done, participants had the option of a 15-minute break. In the final part of the second session participants filled out control questionnaires and were debriefed.

Participants were strongly urged not to discuss the content of the tasks with each other between sessions. The incentive system consisted of a complete report providing feedback on the performance in each of the different tasks and cash payment according to performance. All participants were paid on the afternoon after the last session was over.

3.2 Tasks

I used different tasks to operationalize each of the key variables in the model. The tasks allowed me to assess each individual’s performance through observed behavior providing a more reliable and accurate assessment than the one I would obtain using for example self-reported measures. For a summary of the constructs and tasks presented in this section, and the measures presented below in section 3.3, please see Table 1.

3.2.1 Strategic decision-making task. I looked for a realistic task that would simulate a dynamic organizational business scenario with enough information and complexity to exceed the decision-makers' cognitive limits. In particular, the scenario needed to force participants to consider a number of key business challenges concomitantly, including timing, uncertainty about market information, and levels of investment in real organizational settings. I used Christensen and Shih's online 'Strategic Innovation Simulation' (2008). The participant faces the innovator's dilemma: has to balance R&D investment trade-offs between sustaining investment in the unit's existing business versus investing in a new, potentially disruptive one. The participant manages R&D portfolios over eight simulated years. The objective is to maximize the cumulative profit. The participant must decide which market opportunities to pursue, each of which offers varying levels of market intelligence and differing short- and long-term payoff prospects. After the participant takes each year's decisions, the simulation computes several variables and replicates a dynamic organizational context.

This game simulates an ideal decision-making setting for this research, since it incorporates fundamental features and complexities characteristic of how strategic decisions related to innovation are done in organizations. Throughout the simulation the participant is confronted with timing issues, levels of investment across both mature and new businesses, choices regarding market opportunities and inherent product performance characteristics, the need to meet constraining financial objectives, and constant trade-offs between investment options – all in the context of uncertain market information. The simulation also provides the participant with detailed feedback on the organization's performance as the participant's decisions interact with simulated organizational and market variables.

The suggested time for playing varies from 45 minutes to two hours. Participants were allowed to take as much time as they wanted. All of them finished the simulation well within the maximum allowed time of 2.5 hours.

3.2.2 Routinization task: In order to observe routinization in a context of individual decision-making, I relied on a simple decision-making task: the 'four-armed bandit' gambling game as developed by (Daw et al. 2006). This game involves repeated choices between four slot machines that pay off points. The task consisted of four sessions of 75 trials each, separated by a one-minute break. On each trial, participants were presented with pictures of four slot machines. They had to select one in a short period of time[6]. After selecting one of the four options, the payoff of

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[6] Subjects had a maximum of 1.5 seconds in which to make their choice; if no choice was entered during that interval, a large red X was displayed for 4.2 seconds to signal an invalid missed trial (after which a new trial was triggered). Subjects usually responded well before the timeout. On valid trials, the chosen slot machine was animated and, three seconds later, the number of points earned was displayed. These points were displayed for 1 second and then the screen was cleared. The trial sequence ended 6 seconds after trial onset, followed by a jittered intertrial interval using a discrete approximation of a Poisson distribution with a mean of 2 seconds, before the next trial was triggered.

that slot is revealed. The objective is to maximize the cumulative payoff. Each slot pays points around one out of four different means[7]. The payoffs each slot pays changed from trial to trial. The payoffs were predefined, and all participants were given the same sequence of 300 trials. Participants find information about the payoff of a slot only through active sampling. In pilot tests I corroborated that while playing the game participants created routines for choosing between the slots.

After playing the four-armed bandit gambling game, the participants were debriefed. An open-ended request was presented on the computer screen after the game was over. The exact wording was ‘Please describe the general strategy you followed while playing’. Participants had no limitations in terms of available time or writing space. The coding strategy used to measure the extent of routinization is explained in appendix 7.2.

3.2.3 CCCs tasks: I chose five different tasks to observe the main facets of the four different functional components of CCCs described in section 2.2. Each task emphasizes a particular mechanism:

1) **Flanker task:** this test (also called Eriksen) assesses attention control, the ability to selectively focus attention on relevant information even in the face of distracting or competing stimuli and to sustain attention, maintaining a consistent response during

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[7] The payoff for choosing the ith slot machine on trial t was between 1 and 100 points, drawn from a Gaussian distribution (standard deviation $\sigma_o = 4$) around a mean $\mu_{i,t}$ and rounded to the nearest integer. At each timestep, the means diffused in a decaying Gaussian random walk, with $\mu_{i,t+1} = \lambda\mu_{i,t} + (1 - \lambda)\theta + v$ for each i. The decay parameter λ was 0.9836, the decay center θ was 50, and the diffusion noise v was zero-mean Gaussian (standard deviation $\sigma_d = 2.8$). All participants were exposed to the same distribution of the payoffs.

continuous and repetitive activity (Eriksen 1995; Sanders and Lamers 2002). In this task, participants have to respond as quickly as possible to a centered and directed item (i.e. an arrow pointing to either right or left) juxtaposed with distracting symbols (i.e., arrows pointing in other directions). The distracters can be congruent (i.e., arrows pointing in the same direction of the central arrow), incongruent (i.e., arrows pointing in the opposite direction of the central arrow) or neutral (i.e., no distracter).

2) **N-back task:** The N-back task (Kirchner 1958) is used to assess working memory. Despite the name, working memory is not actually a type of memory, but rather a supervisory ability to keep different pieces of information in mind, ready to be used, manipulated, compared or related (rather than passively stored). Working memory has been previously associated to the ability to draw analogies (Morrison and Cho 2008; Morrison and Richland 2010). In the N-back task, the participant is presented with a sequence of stimuli (i.e., letters) and has to indicate, under time pressure, when the current stimulus matches the one from *n* steps earlier in the sequence. The load factor *n* can be adjusted to make the task more or less difficult. For example, in the ‘two-back task’, the participant has to compare the current letter with the one that was presented two steps earlier in the sequence, while also remembering it for comparison with the letter that will appear in two steps’ time.

3) **Tower of Hanoi:** The Tower of Hanoi task (devised by Edouard Lucas in 1883) measures planning and generativity abilities, considered a central part of CCCs. The participant is asked to generate causal relations and anticipate consequences, and so create alternative paths of action. The task presents three rods and a number of

disks of varying sizes that can be slid on to any rod. In the task the puzzle started with three disks neatly stacked in order of size on the leftmost rod, the smallest at the top, forming a conical shape. The objective of the test was to move the entire stack to the rightmost rod, obeying three rules. First, only one disk could be moved at a time. Second, each move must consist of taking the upper disk from one of the rods and sliding it onto another rod, on top of the other disks that may already be present on that rod. Third, no disk could be placed on top of a smaller disk. The goal is to transfer the disks to the rightmost rod in the smallest possible number of moves and the shortest time. Participants tend to move the disks without enough planning, which increases not only the number of moves but also the final response time.

4) **Cognitive Reflection Test (CRT):** This test measures emotional self-regulation or ‘cognitive reflection’ – that is, the ability or disposition to resist reporting the response that first comes to mind (Frederick 2005). Similar to the Need for Cognition scale (Cacioppo and Petty 1982), this test relates to an individual tendency to engage in thinking. However, the need for cognition relies on self- reported behavior while the cognitive reflection test measures observed behavior. Participants are presented with a series of simple problems which solutions’ are straightforwardly understood when explained. However, reaching the correct answer often requires the suppression of an erroneous answer that springs immediately to mind. The problems vary in difficulty. Answering correctly requires the ability to self-control the impulse to respond before thinking the answer through.

5) **Raven matrices:** Raven's progressive matrices evaluate abstract thinking (Raven et al. 2003). The test presents a pattern of eight related images. The participant must identify the missing segment required to complete the larger pattern, in a multiple-choice format. The questions vary in difficulty, requiring different levels of abstract thinking.

3.3 Measures

3.3.1 Dependent variable: Decision-making performance

I used the cumulative profit over eight simulated years to measure decision-making performance. This measure is suggested as comprehensive by the creators of the simulation (Christensen and Shih 2008). To achieve high performance, the participant needs to balance financial goals against the need to innovate, capitalize on new product/market opportunities, and guard against disruptive technologies. They must take into account resource requirements, product performance, investment timing, and end-market opportunities for a new technology in the context of nebulous market information and constraining financial performance criteria.

3.3.2 Independent variables: Routinization

I measured routinization in two ways.

First, I coded and content-analyzed each participants' reported strategy for playing the game. I asked all participants, after playing the gambling task: 'Please describe the general strategy you followed while playing'. On this basis, I constructed the measure '*routine features*' that captures the extent to which the participant's description of their strategy conforms with previously recognized features of field-observed routines. I followed previous literature which has characterized routines in terms of repeated action sequences, reliability, occasional suboptimality, and increased speed (Cohen and Bacdayan 1994). For each participant I counted how many of these four features appeared in their own description of their strategy, thus generating a measure of routinization (ranging from 0 to 4). The analysis of self-reports has been widely adopted to study routinization; for a review, please see Betsch et al. ((2001), p. 26-27). A summary of the procedures and the related analyses is presented in Appendix 7.2.

Second, since the speed of task performance has been identified as a principal indicator of routinization (Cohen and Bacdayan 1994; Weiss and Ilgen 1985). I measured the time it took participants to play each of the 300 trials in the routinization task and calculated each participant's average response time.

The first measure confirms that the procedures developed by the participants had the features previously mentioned in the literature under the label of 'routines' (i.e. repeated action sequences, reliability, occasional suboptimality, and increased speed (Cohen and Bacdayan 1994)). The second measure provides an indicator of speed, which past literature has associated with the use of routinization (Cohen and Bacdayan 1994, Eisenhardt 1989).

3.3.3 Independent variables: CCCs measures

For each of the five tasks I used to observe the different facets of CCCs I extracted several well established measures for each task.

1) Flanker task measure: I used the average response time and the number of correct answers to the different types of trials (congruent, incongruent, and neutral). I also calculated an index of ‘net speed’ in the response time by subtracting the congruent response time from the incongruent response time. This index provided a pure measure of attention control: the lower the difference in the response time between the incongruent vs. the congruent trials, the higher the attention control.

2) N-back measures: I used the average response time and the number of correct answers to the ‘two-back’ and ‘three-back’ tasks.

3) Tower of Hanoi measures: I measured the total response time and the number of moves it took each participant to finish the task. If a participant did not finish, I took into account the number of moves they had made when their time elapsed.

4) Cognitive reflection test (CRT) measures: I used the three main questions from Frederick (2005) and added seven similar questions that I created and pre-tested in several pilot tests. I measured the average response time and the number of correct answers to the set of three main questions, and to the additional seven questions. The participants’ performance was very correlated, but I kept the two sets of measures separate nonetheless.

5) Raven Matrices measures: I randomly chose ten questions from the broader set of questions in the original Raven test (Raven et al. 2003). I measured the total response time and the total number of correct answers.

3.3.4 Controls

I controlled for participants' gender and age. To comply rigorously with neuropsychological studies, and since stress can interfere with the functioning of the attentive system and the type of cognitive abilities involved in CCCs, I also controlled for levels of stress and anxiety. I used the Stress and Trait Anxiety Inventory (STAI), a widely used test for measuring anxiety in adults. It differentiates between the temporary condition of 'state' anxiety and the more general and long-standing condition of 'trait' anxiety. Each condition has 20 items, each with four possible responses. In addition, I controlled for personality traits, measuring temperament and character with the TCI-56 (Cloninger 1994) , though I do not report these results in this paper for the sake of brevity. This personality inventory has 56 items on five-point scales (1=total disagreement, 5=total agreement). No differences were found in the variables of interest of this study.

Insert Table 1 about here

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4. Results

In this section, I first provide descriptive statistics on the different measures. Second, I summarize the results of preliminary analyses of the independent variables: routines and CCCs. For the routines, I present the key results of the analyses carried out to interpret the qualitative data from the debriefing self-reports and its relation with the response time measures. For the CCCs, I present the results of the factor analysis carried out to summarize the five tests' measures. Third, I present the main correlations found between the measures of routinization and CCCs.

These relate to the first two hypotheses. Finally, I summarize the regression models and bootstrapping approach and integrate the results.

4.1 Descriptive statistics

Table 2 presents the number of answers analyzed, means, standard deviations, and minimum and maximum values for each of the study measures.

Insert Table 2 about here

4.2 Routinization

In this section I report the key findings of the analyses performed to understand the relationship between the two measures of routinization: extent and response time. In coincidence with previous studies, the analyses of the self-reports confirmed that the task allowed most participants (83%) to develop repeated action patterns (Daw et al. 2006). Moreover, those *recurring action patterns* were characterized and varied in terms of reliability (the repeated sequences of actions led participants to acceptable results), occasional suboptimality (the repeated patterns of actions led to good choices in many but not all cases), and speed (the repeated patterns of actions led participants to speed up their decisions).

The measure *routine features* is negatively correlated (-.261 p=0.021) with the response time in the gambling game. That is, the participants whose descriptions of the procedures had more features corresponding to routines (i.e. those who mentioned more of the above mentioned routines' features; Cohen and Bacdayan 1994) were significantly quicker at making decisions (i.e., they had a lower reaction time). Therefore, the participants who developed a routine were quicker than those not who did not. An extended explanation of the analyses can be found in the appendix 7.2.

Taking into account the analyses and findings summarized in this section, I will use the response-time measure as the proxy variable for routinization for the remainder of this paper. This measure is advantageous for three main reasons. First, because it is correlated to the qualitative descriptions obtained about the different types of patterns developed by participants (p=0.05) and with the number of routine-like features displayed by participants' behavioral patterns (p=0.021, as mentioned before). For an extended explanation please see Appendix 7.2, in particular tables A4, A5 and A6. Second, the response-time measure is not categorical, but unique to each participant, which facilitates more fine-grained analyses. Third, this measure is available for the all the participants, even for the 10 self-reports that were not included in the analyses because they were not clear enough.

4.3 CCCs factor analysis

The five tests used to measure CCCs (described in section 3.2 under the title 'CCCs tasks') produced 18 variables. In order to group them under meaningful factors, I performed an exploratory factor analysis (Principal Component Analysis, varimax rotated solution, maximum iterations for convergence=50 and missing values excluded cases listwise. Same results hold usig Oblimin analyses). Each of the factors groups together variables that correspond to a functional component of the CCCs. Two functional components are represented into two factors each. One factor corresponding to measures related to performance and another factor corresponding to measures related to speed of response. This leads to a total of six factors that group 17 variables[8] and account for 72.27% of the variance (please see Table 3 below).

Factor 1 (attention control) groups four measures that reflect the ability to focus on relevant information and maintain attention on selected information while avoiding being distracted. The four items are the speed in answering to the incongruent, congruent, and neutral stimuli in the flanker task, plus the net measure derived from subtracting the speed of response to congruent stimuli from the speed of response to incongruent stimuli.

Factor 2 (reflective capacity) groups five measures related to participants' performance in different subsets of questions in the cognitive reflection test, as well as their speed of response. Also included are the performance and speed measures in the Raven Matrices test. This factor reflects the ability to resist reporting the first thing that comes to mind, and instead engage in abstract thinking to determine the correct answer. Interestingly, and supporting the validity of the factor, I note that the two variables related to the speed with which participants answered the Raven matrices and the Cognitive reflection test correlate with their respective performance

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[8] I took out 1 of the 18 variables because of its low load. The excluded variable was the number of correct answers to the Flanker congruent stimuli (its load was 0.47 which was below the 0.5 threshold that I used).

measures in opposite ways. Those who answered the Raven matrices quickly did better on the test measuring abstract thinking, while those who took more time to answer to the cognitive reflection test displayed a superior reflective capacity.

Factor 3 (planning and generativity) groups two variables that measure the ability to make causal relations, generate alternatives, and anticipate the consequences of plans: the speed at which the participant solved the tower of Hanoi problem, and the number of moves they required.

Factor 4 (output of attention control) relates to Factor 1, but reflects the ability to answer questions that require attention control. This factor groups the variables that measured the number of correct answers to neutral and incongruent type of stimuli in the flanker task.

Factor 5 (working memory speed) groups two variables that measured the response time of the correct answers provided to the ‘two-back’ and ‘three-back’ tests.

Factor 6 (working memory performance) groups two variables that measure working memory performance by counting the number of correct answers to the ‘two-back’ and ‘three-back’ tests. It makes sense that the factor analysis found two different components underlying the variables related to working memory; the variables grouped under Factor 5 are somehow more ‘demanding’, since they only measure the speed of response the participant achieved when answering correctly. Factor 6 instead captures the ability to correctly answer to the test, independently of time taken. A correct answer shows a better working memory capacity, which means the participant is better at holding multiple pieces of information uppermost in their mind. Also, as stated, working memory is not actually a type of memory, but the capability to keep different pieces of information in focus and process them. One's working memory is even better if, as captured by Factor 5, one is able to answer correctly and quickly. As these six factors capture different aspects of the CCCs, I shall use them as my proxy for the level of CCCs.

Insert Table 3 about here

4.4 Correlation analyses

Correlations between the independent, dependent, and control variables for the sample are reported in Table 4. First, in line with Hypothesis 1, the measure of routinization (response time in the simple decision-making task) correlates strongly and negatively ($p<0.01$) with decision-making performance. Second, I find that decision-making performance correlates significantly with Factor 6, i.e. working memory performance ($p<0.05$). As described before, working memory is a cognitive ability that requires activating a broad attention span to actively keep in mind different pieces of information ready to be used, manipulated, compared or related. None of the other five factors was significantly correlated with the dependent variable. Still, all correlations exhibit the expected sign. proposed in hypothesis 2: the stronger the decision maker's CCCs, the better the decision-making performance.

I also found that two factors constituting the CCCs are highly correlated with routinization. First, the routinization measure correlates strongly[9] with Factor 1 (attention control $p<0.01$). That is, the higher the attention control (given by a low response time in the Flanker measures), the greater the routinization. Second, routinization correlates strongly and negatively[10] with Factor 6 (working memory performance, $p<0.01$): the better the working memory, the greater the routinization.

Insert Table 4 about here

4.5 Regressions results: routinization mediates CCCs' relationship with performance

Table 5 summarizes the results of the OLS estimates from multiple regression analyses. First, I specify a model with four control variables: age, gender, state of stress and anxiety, and trait of stress and anxiety, as these variables may influence the cognitive abilities (Controls model in Table 5). I include these four control variables in all the models that follow. For the sake of brevity I do not include in the regressions the variables related to personality, as they have no effect on any of the variables of interest.[11] Second, to test hypothesis 1, I specify model 1, including the control variables and routinization. Hypothesis 1 is supported: the higher the level of

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[9] Please note that the interpretation of the correlation coefficient is direct, since both measures of routinization and of attention control are response times.

[10] Please note that if we talk about "routinization", the interpretation of the correlation coefficient is the opposite from when we talk about response time, since a high routinization implies a low response time.

[11] There are strong gender differences in the dependent variable. Men routinized more and did better than women in the managerial decision-making simulation. This is a puzzling result that we discuss in appendix 7.3

routinization (the lower the response time), the better the decision-making performance.

Third, to test hypothesis 2, I specify a model with the control variables and the six factors that represent the different aspects of the CCCs (model 2). Factor 3, ’planning and generativity’, and Factor 6, ‘working memory performance’, show significant correlations with the dependent variable: decision-making ability. This provides partial support for hypothesis 2 (the stronger the decision maker’s CCCs, the better the decision-making performance). First, the ‘planning and generativity’ ability – i.e. the ability to make causal relations, imagine alternatives, plan an optimal sequence of actions and implement it – turns out to have a direct impact on decision-making performance. Also, working memory performance – i.e., the ability to have different pieces of information under the scope of attention and be able to actively relate them – appears to be related to the performance obtained in the decision-making task.

To test Hypothesis 3 (the higher the level of routinization of individual decision-making, the stronger is the link between CCCs and decision-making performance), I create six interaction terms corresponding each to the product of one of the six CCCs factors multiplied by the routinization measure (Baron and Kenny 1986). Model 3 tests the same model as Model 2, and adds to it the routinization indicator and the six interaction terms. Only one of the six interaction terms is significant: ‘working memory output’. Besides, the variable routinization is also significant. These findings provide only very weak support for Hypothesis 3.

Insert Table 5 about here

Finally, to test Hypothesis 4 (the level of routinization mediates the impact that CCCs have on decision-making performance) I specify two models (Baron and Kenny 1986; Zhao et al. 2010). In the first model, the dependent variable is the extent of routinization (model 4). I keep the same independent variables as in model 2: the control variables and the six factors representing the CCCs. Interestingly, the significance level of the ‘working memory performance’ and ‘planning and generativity’ factors improves. In addition, Factor 1, ‘attention control’, significantly predicts the routinization. Next, I specify model 5. The dependent variable is decision-making performance and the independent variables are the control variables, the six CCCs factors and the variable measuring routinization. Crucially, adding the routinization not only impacts the effect of the CCCs on the dependent variable, as predicted by Hypothesis 4, but it completely eliminates it. I interpret this result as evidence in favor of Hypothesis 4, i.e. I find a full mediation effect: the ability to routinize completely mediates the effect that CCCs have on decision-making performance. Apart from using the criteria prescribed by Baron and Kenny (1986), I also evaluated the significance of the mediated effect using both a Sobel test and a bootstrapping approach (Zhao et al. 2010). The Sobel test has problems in small samples. Its two-tailed p value is based on the assumption that the distribution of the indirect effects follows a normal distribution under the null hypothesis. This assumption has been seriously questioned. Not only is the distribution not necessarily normal, often it is not even symmetrical, especially in small samples (Bollen and Stine 1990; Zhao et al. 2010). Because the distribution of products is usually positively skewed, the symmetric confidence interval based on the assumption of normality will typically yield underpowered tests of mediation. If access to raw data is possible, an recommended approach is to bootstrap the sampling distribution of the indirect effects and derive a confidence interval with the empirically derived bootstrapped sampling distribution (Zhao et al. 2010).

Insert Table 6 about here

I used the Preacher And Hayes (Preacher and Hayes 2008) bootstrapping SPSS macro for estimating indirect effects in mediation models to estimate the confidence intervals for each of the three CCCs factors (Attention control, Working memory and Planning and generativity) which affect the dependent variable (decision-making performance). Preacher And Hayes (2008) macro allows to include covariates so I included the same variables as in the regressions (i.e. on each case the other 5 CCCs factors, and the control variables age, gender, state of stress and anxiety, and trait of stress and anxiety). The 95% bias-corrected bootstrap confidence intervals were obtained using 5000 bootstrap samples.

Table 6 presents the Sobel test and bootstrap results which are highly consistent. The Sobel test underpowered the evidence of a mediation from factor 3.

Since zero is not in any of the 95% confidence intervals. I can conclude that the indirect effects of the three CCCs –Attention control, Working memory and Planning and generativity- are indeed significantly different from zero at p<0,05 (two tailed).This is a crucial finding as it helps understanding how CCCs (and what kind of CCCs in particular) support routinization. Figure 2 depicts the findings.

Insert Figure 2 about here

4.6 Reliability checks

As a reliability check of the findings, I ranked participants according to their performance on the dependent variable: decision-making performance. Then I divided the sample into three groups. The first grouped the best 29 participants in the decision-making task, the second grouped the 29 average performers and the third the 30 worst performers. I then calculated the average response times on each of the four-sessions of the gambling task for each of the three groups. In diagram 2 below, on the vertical axis I show the measure of routinization, i.e. the response times in the simple decision-making task (the gambling game). On the horizontal axis, the evolution of the routinization can be seen for the 300 trials divided into the four sessions: 1) 1 to 75, 2) 76 to 150, 3) 151 to 225 and 4) 226 to 300.

In line with the fact that most participants routinize, I observe that, on average, response time diminishes during the game (see figure 3). However, high performers in the decision-making task developed and enacted routines faster than low performers. Interesting, since the beginning, high performers had significantly lower response times compared to average and low performers. It is possible to observe how, throughout the task, the gap among their response time and that of the other two groups became even wider. I interpret this finding as supporting evidence for Hypothesis 4. CCCs, and particularly the 'working memory performance', 'planning and generativity' and 'attention control' factors of CCCs, enable participants to anticipate the unfolding of events and thus develop simple rules that explain the reduction in their response times.

The best performers also kept on routinizing during the whole game. Apparently they 'exploited' the routine and thus achieved faster response times during the rest of the game. In contrast, the response times of poor performers initially decreased, but increased again during the last 75 trials.

Insert Figure 3 about here

4.7 Routinization and CCCs

To further verify the findings and gain additional insight, I assigned participants to one of four conditions depending on their routinization ability and their scores on the two CCCs that were highly correlated with decision-making performance. To simulate the four conditions, I first created a new measure by adding up each individual scores in the two factors that had a significant impact on decision-making performance: 'planning and generativity' and 'working memory performance'. I then split the sample into two according to whether each participant's score in the new measure was above or below the mean. Then again, I divided each of the two groups into two subgroups depending on whether each participant's measure of routinization was above or below the mean. I thus obtained four possible conditions according to whether the participant ranked below or above the mean on the two CCCs that had a significant impact on performance an on the routinization variable. The first group clustered the participants who had low scores in Factors 3 and 6 and low routinization ability. The second group clustered those participants who had high scores in Factors 3 and 6 and low routinization ability.. The third group clustered those who had low scores in Factors 3 and 6 and high routinization ability. The fourth group clustered those who had high scores in Factors 3 and 6 and high routinization ability. I then calculated for each group the mean in the decision-making task. The differences in the means are significant (p=0.006).Figure 4 shows the average profit obtained in the decision-making task for each of four groups. This result further corroborates the discussion about Hypothesis 4. CCCs per se do not explain superior performance: participants with high routinization scores but low CCCs (Factors 3 and 6) actually outperform participants with high CCCs (Factors 3 and 6) but low routinization scores. CCCs per se have a weak direct effect on performance, which is consistent with the logic behind Hypothesis 4 (and models 4 and 5).

The direct effect of the CCCs embedded in ‘working memory’ and ‘planning and generativity’ disappears when routinization is taken into account. Why? Because it is captured in the individual's ability to create repetitive patterns of action. As stressed by Nelson and Winter (1982), routines are the solution to problems solved in the past (i.e. plans) and are a powerful memory tool (i.e. to keep important elements under attention as does working memory). Once introduced in the model, they crowd out the ‘working memory performance’ and ‘planning and generativity’ factors. Why should it be that those individuals who have high CCCs (Factors 3 and 6), but do not routinize, are worse off than those with low CCCs who do routinize? A plausible explanation is that without ‘attention control’ (the factor that appeared to be highly correlated to routinization, but not directly to decision-making performance), decision-makers with high CCCs (Factors 3 and 6) could not cope with the complexity of decision, as they were unable to focus and subsequently sustain their attention on relevant pieces of information. In other words, they had cognitive breadth, but not depth. They could see all the elements of the decision-making task, but could not selectively focus their attention on the few, crucial variables. Hence, their overall performance was relatively low.

Insert Figure 4 about here

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5. Discussion

This paper focuses on the role that cognitive control capabilities and routinization play in explaining decision-making performance. The initial finding in this paper is encouraging but not surprising: both are important to maximize the performance of decisions. Some of the other findings, however, reveal novel evidence on how the two processes influence each other in their impact on decision-making performance. Even though the debate in the extant literature has thus far focused on the moderating role of routinization in enhancing the effectiveness of CCCs (Cohen et al. 1996; Levinthal and Rerup 2006a), the data that I analyzed support the idea that routinization acts as a full mediator between CCCs and performance. The effectiveness of CCCs is largely explained by its influence on the development and adaptation of routines, which in turn enhance decision-making performance.

This result is somewhat at odds with Weick and Sutcliffe's (2006) suggestion that stability and vividness of attention lead to mindfulness. They argue that when unexpected events arise, the ability to sustain attention is interrupted, leading to poor performance – essentially, a moderating effect of routinization on the effectiveness of higher cognitive capacity (Hypothesis 3). In the data, Attention control does not have a direct impact on performance, but is highly correlated with the ability to develop and adapt routines. In addition, the evidence that I examined allows to be more precise about the specific dimensions of mindfulness that seem to matter in the chain that links CCCs to decision-making performance, through the mediation role of routinization processes. I find, in fact, that the 'planning and generativity' and the 'working memory' dimensions have a direct impact on decision-making performance in the absence of routinization, and that they are fully mediated by the role of routinized behavior, once this latter factor is entered into the model.

The tension between different ways to conceptualize the relationship between cognition and behavior, represented in Hypotheses 3 and 4, has been a subject of discussion for a long time (Gavetti and Levinthal 2004). The full mediation role of routinization between cognitive capacity and performance, offers a novel way to understand the role of less mindful processes in complex decision-making contexts. This view is consistent with intuitions by some of the early thinkers of modern psychology (Whitehead, 1911; Dewey, 1922) as well as with the most recent advancement in neuroscience on the pervasive role of neuroplasticity(Goldberg 2001).

As early as 1911, Whitehead anticipated what psychological research discovered many years later: the limitations of self-regulatory capabilities (Baumeister et al. 1998).

> “It is a profoundly erroneous truism, repeated by all copy-books and by eminent people making speeches, that we should cultivate the habit of thinking of what we are doing. The precise opposite is the case. Civilization advances by extending the number of operations which we can perform without thinking about them. Operations of thought are like cavalry charges in a battle—they are strictly limited in number, they require fresh horses, and must only be made at decisive moments” (Whitehead 1911, p.61).

This is precisely what I find in this study: decision-makers who rely on routinization outperform those who do not. Moreover, routinization is not the product of shallow rationality, as is often implied in debates on the merits (and demerits) of routinized behavior. On the contrary, it is the product of higher cognitive capabilities: decision-makers who have strong CCCs tend to be faster in developing and applying routines, which gives them a double advantage in a complex decision setting. Not only are they more likely to frame the problem more quickly than their peers with lower CCCs levels, but they can translate their superior clarity of mind into better and faster routinized behavior, thus compounding the advantages of both factors.

These results may have important implications for the management of teams. For example, these results suggest that in order to leverage on different individuals' abilities, when teaming up people, managers should account for individuals' strengths in CCCs and routinization. It may be important to have either several individuals who are able to act blending together high levels of CCCs and of routinization, or else to group together individuals who are more prone to routinization with individuals who have strong CCCs.

The implications of these evidence for evolutionary theories of organizations and learning could be profound. First, the virtuous role of routinization in decision-making, one of the fundamental tenets of evolutionary economics (Nelson and Winter 1982) is empirically validated. Second, the conceptual and empirical inquiry is carried out at the individual level of analysis, contributing to the development of micro-foundations for the standard claims at the group or organizational levels. Third, the fact that the full mediation of routinization on the effectiveness of CCCs was found to be a better description than a moderating role means that the benefits of routinization might extend even further than originally conceived in Nelson and Winter's (1982) formulation of the theory. When routinization processes are entered into the model, the quality of cognitive capacities loses its relevance as an antecedent of strategic decisions' performance, which can be interpreted to mean that there is a significant component of rationality and cognitive capacity in the selection and enactment of routinized behavior.

At the same time, the fact that cognitive capabilities are at the origins of routinization lends credit to the claims of the 'mindfulness' school (Langer 1989; Rerup 2009; Weick and Sutcliffe 2006; Weick et al. 2005) on the role of attention-control capacity in the generation of appropriate behavioral outcomes, especially in complex and ambiguous decision-making contexts. Whereas Whitehead's quote emphasizes the need to routinize, the consequences of routinizing in inappropriate situations can be disastrous (Gersick and Hackman 1990; Levinthal and Rerup 2006a).

The evidence examined suggests, therefore, that a crucial challenge for managers and their organizations is the ability to blend together mindful and less-mindful behaviors. In Levinthal and Rerup (2006)'s words, 'learning is a mindful exercise of appropriately mapping routines to a context'. The interplay between the two processes can be described from several perspectives. First, as supervisory mechanisms, CCCs are responsible for the non-automatic components of the decision related to the triggering of the routines. They help people to change gears from off-line to on-line learning (Gavetti and Levinthal 2000) or from contemplation to action (Louis and Sutton 1991). Also, CCCs might influence the choice of whether to develop or change a routine, based on the framing and cognitive representation of the problem. Second, when a routine response is triggered, CCCs might play a role in directing the enactment of the routines in the most appropriate way: higher CCCs might make a difference between a normal and an excellent execution of the same routine. Finally, CCCs might facilitate better-quality inferences from the performance feedback obtained from the routines' implementation, and thus guide the learning and adaptation processes that constantly shape the evolution of routines through marginal adjustments and trial-and-error processes (Rerup 2009; Rerup and Feldman 2010).

We are still, unfortunately, 'a long way from having an authoritative textbook for students in professional training who want to know how to create effective organizational routines, or how to modify them when they could be still better' (Cohen 2007). It is therefore important to highlight some of the key limitations that I see in this study and suggest some consequent avenues for future research. Caution should be exercised, in fact, in interpreting and generalizing from this study given the characteristics of its sample, the study design, and the pattern of observed findings. First, the use of a single indicator to measure decision-making performance might be a limitation, especially since it is generated by a simulation game. Although this is a thoroughly and extensively validated measure, more reliable and accurate than self-reported measures, the use of a single task remains a weakness to be considered. For example, it would be interesting to study how these results might change in a less innovative context than the one presented in the simulation. One might expect that, in such a context, routinization would acquire even more importance as drivers of appropriate decision-making. In the same way, one may expect that in a purely creative context, CCCs acquire more importance and routinization may, as per the logic explained in hypothesis 3, play a moderating role.

A second limitation is the use of a sample composed entirely by graduate students. Another direction for future research is to replicate this study with managerially experienced participants (Carnevale et al. 2010). This would strengthen the confidence in the robustness of these results.

Also, I presented results based on a cross-section. This study had an observational design, aimed at uncovering the different relationships between mindful and less-mindful abilities. I did not use manipulations, since my objective was to measure individual variation along the various abilities' dimensions, and their concerted impact on performance. Future research could consider the possibility of designing controlled experimental studies that could lead to test the causality dynamics behind these findings.

Finally, I believe that an important avenue for future research is to bring emotions into the picture of the less-mindful and mindful debate. Rationality requires emotional input, but furthermore emotions also guide (or bias) behavior and decision-making (Bechara and Damasio 2005). In fact, both Simon and Dewey included, in addition to cognition and routines (or habits) in their theoretical discourse, emotions as the third element. Future research should also account for emotions as an essential part of strategic decision-making, especially if the objective is to contribute towards the completion of the microfoundations in organizational learning and change theories.

6. Conclusions

> "*Just as philosophical traditions have struggled with the relationship between mind and body (Descartes [1641] 1931), the organizations literature has struggled with an analogous tension between cognitive and behavioral perspectives on action*" (Levinthal and Rerup 2006 p.502).

Mindful and less-mindful processes intertwine, and are both required for achieving superior outcomes. Such intertwining, however, is rather complex, somewhat surprising, and awaits a significant empirical effort from the community of interested scholars to couple the important theoretical debate with a solid grounding in evidence of correlation as well as (and more importantly) causation. I hope that the work presented above has helped shed some light on how to proceed along the path towards more complete microfoundations of the field.

7. Appendixes

Appendix 7.1. Methods – Screening procedure subsection

In order to rigorously comply with the requirements of a neuropsychological study, before joining the laboratory sessions, all potential participants filled out a questionnaire for excluding neuropsychological disorders and the use of drugs or any psycho stimulant.

Also, participants filled out the Circadian Rhythm Questionnaire (Horne and Ostberg 1976) to determine their circadian typologies and diurnal preferences. According to their circadian rhythm, participants were assigned to either a morning or an evening session so that they were at their best cognitive performance time of the day. Two groups were formed. The first group –composed by 38 participants- joined the sessions on two consecutive Wednesday mornings. The second group -51 participants- attended two consecutive Friday evening's sessions. Wednesday and Friday's sessions only differed in the time of the day at which they took place. All participants were asked not to consume any alcohol in the 24 hours preceding each of the sessions. No differences were found between the two groups in any of the study variables.

Appendix 7.2 Routinization analyses and results

In order to uncover possible patterns of behavior among participants' sequences of actions I content-analyzed participants' written self-reports about how they played the four-armed bandit gambling game. The analysis of self-reports has been widely used to study routinization. For a review of studies using this technique, please see Betsch et al. 2001.

After playing the four-armed bandit gambling game, participants were asked to describe (by typing on the PC station where they had just played the game) the strategy they followed while playing. A request was presented on the PC screen after the game was over. The exact wording of the request was "Please describe the general strategy you followed while playing". Participants had no limitations in terms of available time or writing space.

To ensure reliability the analyses were performed separately by two researchers. In eight self-reports the information provided by the participant was not clear enough as to identify the actions that were pursued to play, as in the example below.

"Although it was a gambling game, I tried to find a certain pattern of the numbers appearing in each machine, and I followed a certain order of the machines according to numbers I was getting."

In order to avoid misinterpretations, those 8 cases were excluded from the analyses. In addition, two self-reports were lost due to an error in the program at the time I collected the answers. All the statistics presented here use the remaining 78 self-reports.

To uncover recurring action patterns I followed 5 steps:

1. Routines features
2. Three initial types of procedures followed to play
3. Other procedures
4. Validity and Reliability checks
5. Exclusion of unclear cases

I now describe each of these five steps. Then I summarize the main results obtained from the content-analysis, and how such results relate to the response time measure of routinization.

Step 1: Routines features

First, I read all debriefing reports to develop a general understanding of the main patterns. Participants showed both explorative and exploitative behaviors which coincides with what was reported by Daw et al. (2006), the study from which I replicated the four-armed bandit gambling game. The majority of the participants reported occasionally trying the different slots to work out which currently had the highest payoffs (exploration) while at other times they kept on choosing the slot they thought had the highest payoffs (exploitation).

In this first step I added a “label” depending on which of four possible features characteristic of field-observed routines (Cohen and Bacdayan 1994) was mentioned by the participant. I now explain each of those four possible features.

(1) *Reliability.* The key advantage of routinization has been said to be the increased ability of the organization to produce an acceptable result (Cohen and Bacdayan 1994; Cyert and March 1963). If the participant mentioned that the procedure followed led to good results I added the “reliability” label .

(2) *Speed.* If the participant mentioned that the strategy she/he followed let them to be faster I added a label to their answer regarding this.

(3) *Repeated action sequences.* Another characteristic feature of routines is that the actions are substantially the same over time (Gersick and Hackman 1990). If the participant referred to have followed a repetitive sequence over time I added the “*Repeated action sequences”* label.

(4) *Occasional suboptimality*. A negative side of routines is the tendency for them to "fire off ' in circumstances where, to an observer, some other action would have been more appropriate. I added this label to participants who reported to have

noticed the “cost” of their own routinized behavior. I consider this characteristic particularly interesting as it involves the effort to deal with the trade-off between the cost of the routinization versus the benefits mentioned above.

The table A1 presents how many of the 78 reports that I analyzed mentioned each of the routines features.

Table A1: Features mentioned by participants

		Frequency	%
Occasional suboptimalilty	mentioned	15	19,2 %
	Not mentioned	63	80,8 %
Reliability	mentioned	33	42,3 %
	Not mentioned	45	57,7 %
Repeated action	mentioned	63	80,8 %
	Not mentioned	15	19,2 %
Speed	mentioned	3	3,8%
	Not mentioned	75	96,2 %

I constructed the measure “*routine features*” adding up the number of features a participant mentioned. On average, participants mentioned 1.46 features. Most of the participants mentioned only 1 out of the 4 possible features that I was considering while coding the self-reports (that is to say that the mode was 1).

Step 2: Summary of the three initial types of procedures followed to play

On a second step, I aimed at understanding not only if the participant developed a routine but also *which* type of routine was it. When possible, I classified the descriptions of the procedures followed to play under the 3 types of routines recalled by the participants in the study done by Nathaniel Daw and co-authors whose task I used to measure routinization (Daw et al. 2006). In Daw and co-authors’ study, the strategies followed by participants were classified under three categories from theories on reinforcement learning (Sutton and Barto 2004) regarding how individuals explore any of the 4 different slot machines during the game. Those categories were: “e-greedy”, “softmax” and “awarding bonuses”. Most of the participants’ strategies -65 out of 78- fell under these 3 categories. I describe each of these three categories below:

- **1-greedy**: the simplest method of exploration. The participant chooses the slot he believed to be best most of the time, but occasionally (meaning that the participant does not identify a specific condition according to which he considers unsatisfactory the current machine) substitutes a random action.

> *"At the beginning of each game I tested the payoff of each box, then I selected that box most of the time. During the game a sometimes went for further tests of the odds of the other boxes since the payoff were variable. That maybe was not worth in many cases but there were some reinforces before, that pushed me to test whether I was in the right position too many times maybe"*

- **Awarding bonuses**: in this case, the decision to explore is informative. The actions' payoff are totally uncertain and when the participant identifies the conditions according to which a machine becomes unsatisfactory, he starts to explore in order to identify the second best gamble.

> *"After several trials, one machine will possess high frequency of high points (normally > 60 points). So keep choosing this optimal machine until the point becomes lower than 60 points. Then, try other three machines to find out which one becomes the optimal one."*

- **Softmax**: the decision to explore is determined probabilistically on the basis of the actions' relative expected values. In other words, exploration is guided by expected value. When the participant wants to change the machine, he already knows the gamble to take: according to a personal rule, he is able to identify the second best gamble a priori.

> *"At first, try all the 4 machines to find the one that give me the highest score. Then I continue with that machine till I get scores lower and lower. When the score I get from that machine is lower than other machines, I start with the machine that gave me the second highest score in the first try. And I continue with that second machine till the scores become lower than the other machines. And then I come to the third machine. I also try to change machines occasionally, but I get punished with low scores. So exploring the same machine as much as possible seems to be the best strategy for me"*

Step 3: Other procedures

While most of the participants' strategies fell under the previous 3 categories, on a third step, I searched for similarities that will allow to classify the remaining 13 cases. 2 participants based their decisions on "visual cues". 6 participants kept on trying more than one strategy. 1 participant reported to have followed her intuition on every choice. 4 participants said to have followed no strategy but simply a random choice. I thus created 4 additional categories: “visual”, “random”, “more than one strategy”, and “intuition”. A brief description of each with examples follows:

- “**Visual**” means that the participant chose the strategy to adopt based on a visual criteria, such as the colors, the lines or something similar. In this case, the criteria to perform explorative is based on a relation between these two elements: in other words, the participant thinks that the expected payoff are based on a visual rule.

> *“I choose the machine in relations to the previous point and the possible relations between colors”*

- “**Random**” are those strategies characterized by no selection criteria:

> “*Completely random*”
> “*Stick on one button*”

- **“More than one strategy”**

Under this category I find those participants that mention different strategies without selecting one above others.

> *“- first I tried to choose a machine as quickly as I could I dont think this worked*
> *- if a machine gave high numbers I played it until it decreased to 65 then I tried to switch*
> *- even if 1 machine proved to be good I tried others to see if they were better (usually not)*
> *- when a winning machine started loosing I picked its complement color (at least for blue/yellow) and than back to the winning one.”*
>
> *“Firstly, I gave it some time to get to know the outcomes. I played a bit. Major impression was that values do not vary that much. So I was following the machine with the current highest returns. I also tried some other strategies like keep selecting a machine with lowest returns in hope that they will increased if commitment is made but it did not happen. I also tried to see if sooner or later responses influenced the returns. It did not appear so. I tested the strategy under assumption that the returns are determined according to the set of previous N choices. It did not appear to be so”*

- **Intuition**: a single case was classified as this. Intriguingly, this participant had the highest response time

> *“Follow my intuition”*

Step 4: Validity and Reliability checks

On a fourth step, in order to increase the qualitative validity and reliability of the analyses two researchers checked again –but separately- the appropriate classification of the initial cases that fell under the 3 categories in Daw et al. 2006. The purpose was to be sure that each participant's report was classified under the category that fitted best. After the checks two cases were reclassified..

Step 5: Exclusion of unclear cases

On a fifth step two researchers separately –to ensure reliability- checked again the cases that I could not classify to see whether they fitted any of the categories. As stated before, in eight cases, the information provided by the participant was not enough to identify the actions that they pursued to play. Participants' answers were not so clear as in the cases I classified as "more than one strategy". Nor did they appear to have simply followed a "random" strategy since their explanations assume some logic, however it is not clear the way they played. After analyzing several times the information reported in those eight cases, I decided not to include them in the analyses in order to avoid adding "noise" to the data.

Routinization results

As shown in table A2, on total there were 7 categories that summarized the different behavioral strategies followed by participants:

Table A2: Behavioral strategies followed by participants

		Frequency	%
Valid	Visual cues	2	2,6
	e-greedy	13	16,7
	Awarding bonuses	40	51,3
	Softmax	12	15,4
	Random	4	5,1
	Tries more than one pattern	6	7,7
	Intuition	1	1,3
	Total	78	100,0

Table A3 reports for each of the seven behavioral strategies the average number of *routines features* mentioned by the participants Following what one could expect, the means are statistically different ($p< .000$) and fall into a clear model: *those who acted in a more routinized way mentioned a higher number of features*. On the contrary, those who did not act in a routinized way mentioned a significantly lower number of features.

Table A3: Average routine features by type of procedure

	Type of procedure	**N**	**Mean**	**Std. Dev.**	**Minimum**	**Maximum**
Total of Routines' Features (sig. ,000)	Visual cues	2	0,50	0,71	,00	1,00
	e-greedy	13	1,23	0,83	,00	3,00
	Awarding bonuses	40	1,63	0,77	,00	3,00
	Softmax	12	2,08	0,67	1,00	3,00
	Random	4	0	-	,00	,00
	Tries more than one pattern	6	1,17	1,33	,00	3,00
	Intuition	1	0	.	,00	,00
	Total	78	1,46	0,92	,00	3,00

I then grouped the participants into two groups according to whether the participant routinized. Those who followed a clear strategy and fell into one of the three initial groups proposed by Daw et al. (2006) were labeled “yes” under the new variable “routinized?” Those who did not follow a clear pattern were labeled as “not”. Table A4 shows the mean number of features mentioned by participants of each group is statistically different (p< .000). As expected, the response time was significantly higher in the group of participants who routinized their pattern of actions.

Table A4: Average routine features according to weather the participant routinized or not

Total of routines' features (sig. ,000)	N	Mean	Std. Deviation	Minimum	Maximum
No	13	,6154	1,04391	,00	3,00
Yes	65	1,6308	,80174	,00	3,00
Total	78	1,4615	,92149	,00	3,00

Interestingly, as can be seen in table A5, the two cases following visual cues to decide their strategy were very fast. Those following one of the three initial strategies have lower response times than those following more than one pattern of action. Those following a random pattern were slightly slower than the total average of the participants.

Tesi di dottorato "THE COGNITIVE AND NEUROPSYCHOLOGICAL FOUNDATIONS OF STRATEGIC DECISION-MAKING"

di LAUREIRO MARTINEZ DANIELA
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2011
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Table A5: Average Response time in the gambling game by type of procedure

	Type of procedure	N	Mean	Std. Dev.	Minimum	Maximum
Average Response Time in the Gambling Game (sig. ,050)	Visual cues	2	2.710	1.494	1.653	3.766
	e-greedy	13	2.957	635	1.857	3.789
	Awarding bonuses	40	3.016	787	1.101	4.556
	Softmax	12	3.175	559	2.274	4.042
	Random	4	3.126	667	2.162	3.632
	Tries more than one pattern	6	3.766	565	3.183	4.685
	Intuition	1	4.971	.	4.971	4.971
	Total	78	3.111	762	1.101	4.971

I performed the same analyses but instead of grouping participants under the 7 types of procedures, I grouped them under two according to whether they routinized or not. The result confirms what was found by grouping under the 7 procedures.

Table A6: Routinization measured as following a procedure vs. Response time

Followed a routine vs. Routinization (measured with response time)		N	Mean	Std. Deviation	Minimum	Maximum
(sig. ,043)	no	13	3.499	893	1.653	4.971
	yes	65	3.033	715	1.101	4.556
	Total	78	3.111	762	1.101	4.971

Finally, the total of features a participant mentioned (as said before, a measure constructed adding up the number of routine features a participant mentioned) is negatively correlated (corr.-.261, p=.021) with the response time in the gambling game. This confirms that those participants whose pattern of action had more routine features were faster.

Appendix 7.3 Gender differences

I conducted additional analyses to further check my main findings. I did not find any significant gender differences in the cognitive control capabilities, or in risk or temporal preferences. As by now, different hypotheses may arise. In the first place, psychologists often find that while both men and women are overconfident about their relative performance, men tend to be more overconfident than women (Niederle and Vesterlund 2007). This may lead them to feel the task at hand is under control and so to routinize more, diminishing the time required to answer to the task and improving the performance. I could hypothesize that men tend to show more overconfidence and so they routinize more in the gambling game and improve their performance in the decision-making task.

In addition, another reason to acknowledge for men superior performance in the decision-making task might be differences in motivation. While all participants were apparently very involved in the simulation game and were playing under the same monetary type of reward, it may be that men derived superior motivation from the task itself. Some studies argue that the reason why some studies do not find gender differences is because their tasks are not in the masculine domain (Lundeberg et al. 1994; Niederle and Vesterlund 2007). Some recent research in the neurosciences has found that men show greater activation and functional connectivity compared to females in the mesocorticolimbic system which may be attributable to higher motivational states in males during computer video games(Hoeft et al. 2007). These gender differences may help explain why males are more attracted to, and more likely to be motivated to play computer and video games than females and may also reflect in my task setting where the decision-making simulation and the routinization task kept many of the features of computer and video games. I am currently trying to clarify these issues.

8. Tables and Figures

Table 1: Summary of constructs, tasks and measures

	Construct	Task	Measure
Dependent variable			
Performance	Decision-making performance	Strategic decision-making simulation	▪ Total accumulated profit over 8 years
Independent variables			
Less-mindful	Routinization	Four-armed bandit task	▪ Average response time (seconds) ▪ Extent of routinization (0 low -4 high)
Mindful	CCCs – Attention control	Flanker task	▪ Number of correct responses in each condition. ▪ Average response time in each condition. ▪ Net speed (response time in incongruent trials minus response time in congruent trials)
	CCCs – Working memory	N-back task (versions 2-back and 3-back)	▪ Correct responses ▪ Average response time for good responses
	CCCs – Planning and generativity	Tower of Hanoi	▪ Number of moves ▪ Total response time
	CCCs – Reflective capacity (self-regulation)	Cognitive reflection test (CRT)	▪ Correct responses (two separated measures, one for the first 3 and another for the last 7 questions) ▪ Total response time (two separated measures, one for the first 3 and another for the last 7 questions)
	CCCs – Reflective capacity (abstract thinking)	Raven matrices	▪ Correct responses ▪ Total response time

Table 2: Descriptive Statistics

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Strategic decision-making performance	88	- 476.50	471.20	71.69	167.83
Routinization	88	1,100.85	4,970.85	3,072.66	757.99
2back performance	85	13	35	29.04	5.34
2back Response Time in good trials	85	4,553.97	14,484.55	8,752.54	1,894.54
3back performance	86	7	35	28.79	5.20
3back Response Time in good trials	86	5,162.74	15,737.59	9,536.32	2,224.37
CRT Response Time	88	213.00	1,372.88	495.01	294.31
CRT good answers in first 3 questions	88	0	3	1.49	1.19
CRT good answers in last 7 questions	88	0	7	5.09	1.73
Flanker good answers in congruent trials	87	14.00	32.00	31.56	2.02
Flanker Response Time in congruent trials	87	3,942.03	7,492.07	5,377.39	773.77
Flanker good answers in incongruent trials	85	2	32	29.46	5.11
Flanker Response Time in incongruent trials	87	4,428.91	10,905.33	6,589.67	1,079.29
Flanker good answers in neutral trials	87	29	32	31.80	0.59
Flanker Response Time in neutral trials	87	3,807.50	8,362.13	5,278.98	787.39
Flanker net speed (incongruent minus congruent trials)	87	216.63	3,413.27	1,212.27	568.19
Raven Matrices performance	88	0	9	7.10	1.71
Raven Matrices Response Time	87	136.00	1,766.00	588.02	261.24
Tower of Hanoi number of moves	88	31	326	79.86	46.13
Tower of Hanoi Response Time	88	47	600	291.97	161.15

Table 3: Factor analysis

Rotated Component Matrix	Component					
	1	2	3	4	5	6
Eigen value	3.96	2.34	1.93	1.60	1.40	1.05
% of Variance	23.28	13.74	11.38	9.42	8.26	6.20
Cumulative %	23.28	37.02	48.40	57.82	66.07	72.27
Variables and their loads:	1	2	3	4	5	6
Flanker Response Time in congruent trials	0.931					
Flanker Response Time in incongruent trials	0.959					
Flanker Response Time in neutral trials	0.911					
Flanker net speed (incongruent minus congruent trials)	0.549					
CRT Response Time		0.562				
CRT good answers in first 3 questions		0.640				
CRT good answers in last 7 questions		0.585				
Raven Matrices performance		0.731				
Raven Matrices Response Time		0.679				
Tower of Hanoi number of moves			0.897			
Tower of Hanoi Response Time			0.908			
Flanker good answers in incongruent trials				0.850		
Flanker good answers in neutral trials				0.656		
2back Response Time in good trials					0.869	
3back Response Time in good trials					0.889	
2back performance						0.835
3back performance						0.710

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.

Rotation converged in 6 iterations.

Table 4: Correlations between the dependent variables, the factors and the control variables

Independent Variables: Routinization, Cognitive Control Capabilities and Control Variables		Decision-making performance	Routinization	FAC1_ Attention control	FAC2_ Reflective Capacity	FAC3_ Planning and Generativity	FAC4_ Output of attention control	FAC5_Working memory Speed	FAC6_Working memory performance	control_Year of Birth	control_Gender	control_Anxiety as Trait	control_Anxiety as State
Routinization	Pearson Correlation	-.367(**)	1	.401(**)	-0.115	-0.153	-0.105	0.012	-.333(**)	-0.092	-.220(*)	-0.173	-0.064
	Sig. (2-tailed)	0		0	0.309	0.172	0.35	0.918	0.002	0.395	0.039	0.107	0.556
	N	88	88	81	81	81	81	81	81	88	88	88	88
FAC1_Attention control	Pearson Correlation	-0.011	.401(**)	1	0	0	0	0	0	-0.08	0.032	-0.186	-0.171
	Sig. (2-tailed)	0.923	0		1	1	1	1	1	0.479	0.774	0.096	0.127
	N	81	81	81	81	81	81	81	81	81	81	81	81
FAC2_Reflective Capacity	Pearson Correlation	0.158	-0.115	0	1	0	0	0	0	0.023	0.085	0.051	-0.027
	Sig. (2-tailed)	0.159	0.309	1		1	1	1	1	0.838	0.452	0.649	0.814
	N	81	81	81	81	81	81	81	81	81	81	81	81
FAC3_Planning and Generativity	Pearson Correlation	0.13	-0.153	0	0	1	0	0	0	0.079	-0.091	0.116	.223(*)
	Sig. (2-tailed)	0.247	0.172	1	1		1	1	1	0.485	0.417	0.304	0.045
	N	81	81	81	81	81	81	81	81	81	81	81	81
FAC4_Output of attention control	Pearson Correlation	0.082	-0.105	0	0	0	1	0	0	-0.037	0.037	-0.005	-.261(*)
	Sig. (2-tailed)	0.469	0.35	1	1	1		1	1	0.74	0.74	0.966	0.019
	N	81	81	81	81	81	81	81	81	81	81	81	81
FAC5_Working memory Speed	Pearson Correlation	-0.032	0.012	0	0	0	0	1	0	-0.014	0.128	-0.018	0.006
	Sig. (2-tailed)	0.779	0.918	1	1	1	1		1	0.899	0.253	0.873	0.954
	N	81	81	81	81	81	81	81	81	81	81	81	81
FAC6_Working memory Performance	Pearson Correlation	.259(*)	-.333(**)	0	0	0	0	0	1	0.134	.235(*)	-0.058	0.023
	Sig. (2-tailed)	0.019	0.002	1	1	1	1	1		0.233	0.035	0.606	0.838
	N	81	81	81	81	81	81	81	81	81	81	81	81
control_Year of Birth	Pearson Correlation	0.065	-0.092	-0.08	0.023	0.079	-0.037	-0.014	0.134	1	0.035	0.059	-0.013
	Sig. (2-tailed)	0.544	0.395	0.479	0.838	0.485	0.74	0.899	0.233		0.748	0.588	0.905
	N	88	88	81	81	81	81	81	81	88	88	88	88
control_Gender	Pearson Correlation	.388(**)	-.220(*)	0.032	0.085	-0.091	0.037	0.128	.235(*)	0.035	1	-0.042	-0.113
	Sig. (2-tailed)	0	0.039	0.774	0.452	0.417	0.74	0.253	0.035	0.748		0.696	0.294
	N	88	88	81	81	81	81	81	81	88	88	88	88
control_Anxiety as Trait	Pearson Correlation	-0.001	-0.173	-0.186	0.051	0.116	-0.005	-0.018	-0.058	0.059	-0.042	1	.716(**)
	Sig. (2-tailed)	0.99	0.107	0.096	0.649	0.304	0.966	0.873	0.606	0.588	0.696		0
	N	88	88	81	81	81	81	81	81	88	88	88	88
control_Anxiety as State	Pearson Correlation	-0.094	-0.064	-0.171	-0.027	.223(*)	-.261(*)	0.006	0.023	-0.013	-0.113	.716(**)	1
	Sig. (2-tailed)	0.384	0.556	0.127	0.814	0.045	0.019	0.954	0.838	0.905	0.294	0	
	N	88	88	81	81	81	81	81	81	88	88	88	88

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 5: Regression models

Variables	Controls model	Model 1	Model 2	Model 3	Model 4	Model 5
Constant	(91.61)	(84.109)	(92.404)	(89.443)	(84.558)	(90.530)
Year of Birth	0.045 (0.046)	0.024 (0.042)	-0.002 (0.047)	0.063 (0.045)	0.019 (0.043)	0.003 (0.046)
Gender	.377** (0.211)	0.311** (0.198)	0.344** (0.218)	0.304** (0.213)	-0.160 (0.199)	0.303** (0.217)
Anxiety as Trait	.900 (0.014)	0.029 (0.013)	0.123 (0.015)	0.103 ('.015)	-0.233 (0.013)	0.063 (0.015)
Anxiety as State	-0.122 (0.015)	-0.098 (0.014)	-0.186 (0.017)	-0.237 (0.017)	0.186 (0.015)	-0.138 (0.017)
Routinization		-0.297** (0.101)		-0.275* (0.131)		-0.255 * (0.128)
FAC1 Attention control			-0.031 (0.106)	0.127 (0.117)	0.396*** (0.097)	0.070 (0.116)
FAC2 Reflective Capacity			0.118 (0.105)	0.039 (0.103)	-0.084 (0.096)	0.096 (0.103)
FAC3 Planning and Generativity			0.189 † (0.108)	0.145 (0.108)	-0.184 † (0.099)	0.142 (0.108)
FAC4 Output of attention control			0.021 (0.113)	-0.093 (0.137)	-0.051 (0.103)	0.008 (0.110)
FAC5 Working memory Speed			-0.072 (0.105)	-0.138 (0.108)	0.027 (0.096)	-0.066 (0.103)
FAC6 Working memory performance			0.190 † (0.109)	-0.002 (0.117)	-0.316*** (0.100)	0.110 (0.114)
Routinization x FAC1 Attention control				0.137 (0.120)		
Routinization x FAC2 Reflective capacity				0.129 (0.121)		
Routinization x FAC3 Planning and generativity				0.04 (0.099)		
Routinization x FAC4 Output of attention control				0.03 (0.100)		
Routinization x FAC5 Working memory speed				-0.054 (0.093)		
Routinization x FAC6 Working memory output				0.325** (0.107)		
R2	0.160	0.241	0.248	0.395	0.370	0.288
Adjusted R2	0.116	0.194	0.140	0.231	0.280	0.175
F	3.625**	5.198 ***	2.302*	2.42**	4.10***	2.54**

Notes: † p<0.10; * p=<0.05; ** p=<0.01; *** p<0.001.

Table 6: Sobel estimates and bootstrap confidence intervals for indirect effects on decision-making performance

Antecedents	Mediator	Sobel estimates	Bias Corrected and Accelerated Confidence Intervals 95%
FAC1 Attention control	Routinization	-1.79 *	[-0.289 -0.19]
FAC3 Planning and Generativity	Routinization	1.36 †	[0.0066 0.1730]
FAC6 Working memory performance	Routinization	1.69 *	[0.0191 0.2465]

Notes: † p<0.10; * p=<0.05; Statistical controls included: gender, age, stress as trait, stress as state, and the remaining 5 CCC factors apart from the one being considered as antecedent on each of the analyses.

Figure 1: Hypotheses on Cognitive control capabilities, routinization and decision-making performance

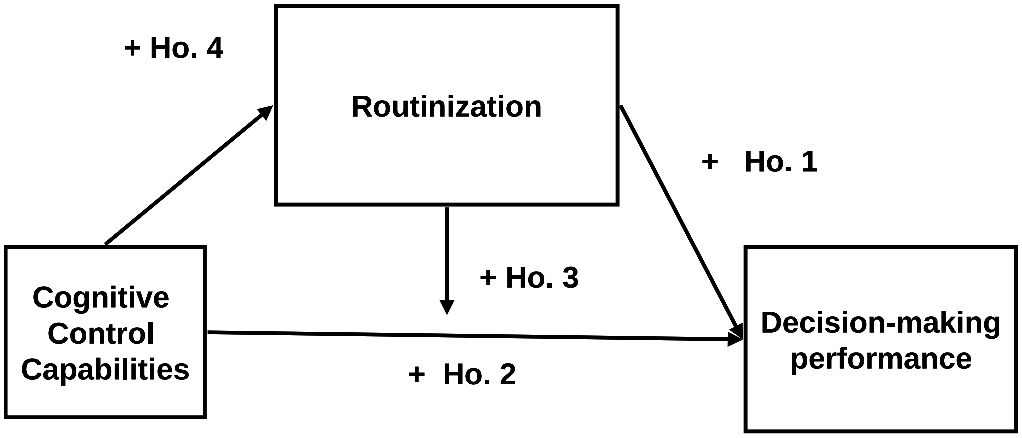


Figure 2: Results Cognitive control capabilities, routinization and decision-making performance

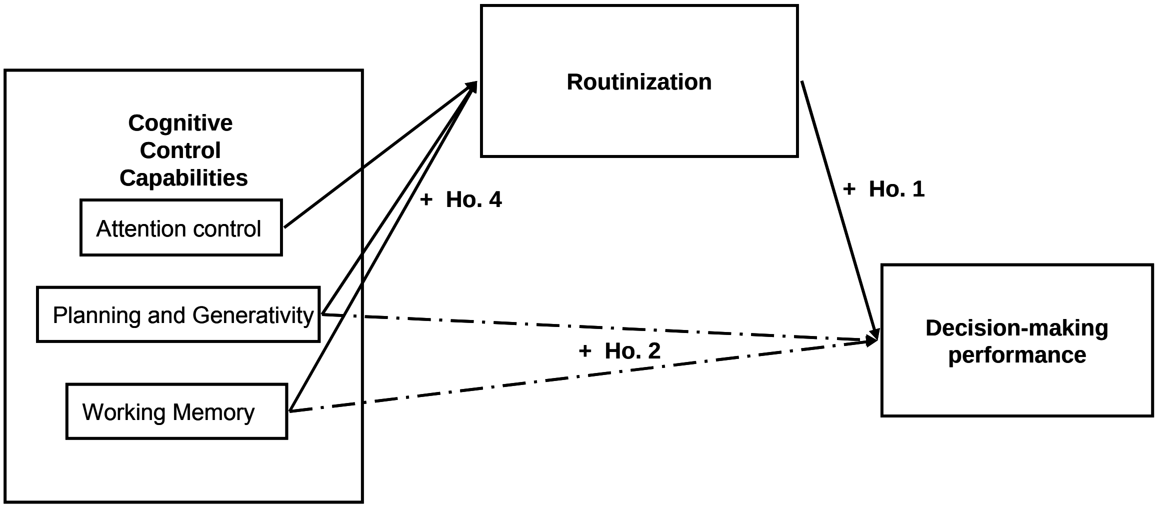


Figure 3: Routinization evolution according to best, average and worst performers

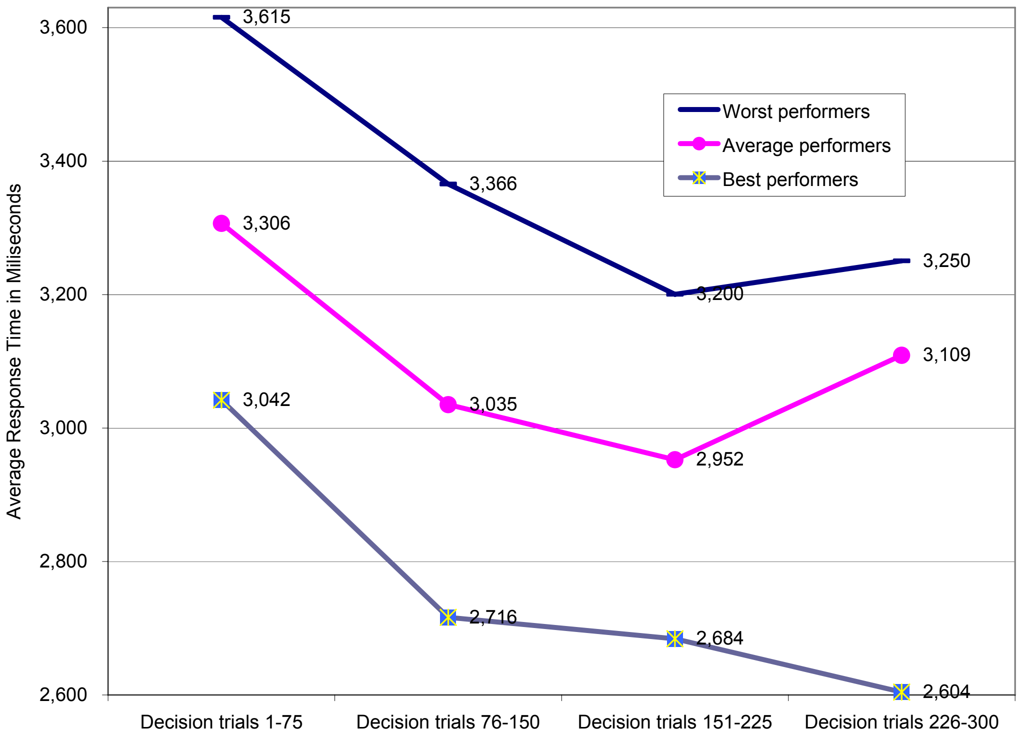
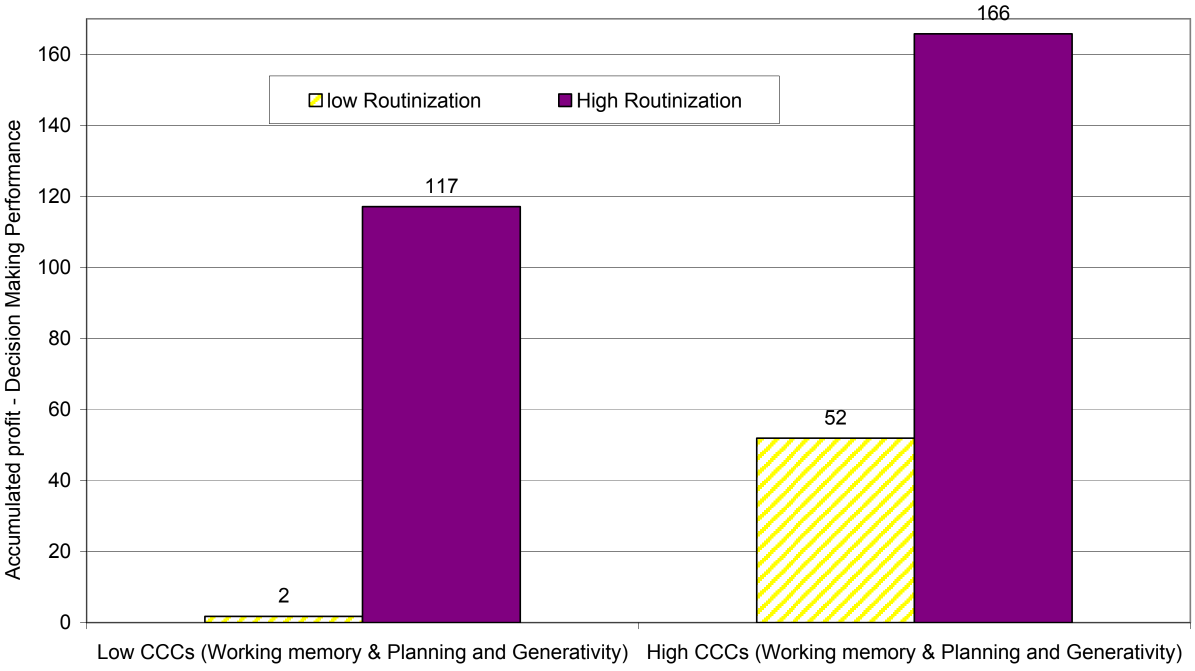


Figure 4: Combined effect of Cognitive control capabilities and routinization on decision-making performance



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The innovative brain: a neural signature

Daniella Laureiro-Martínez[1], Nicola Canessa, Stefano Brusoni, Maurizio Zollo, Federica Alemanno, and Stefano F. Cappa

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[1] **Author contributions**
D.L-M conceived the study. S.B. N.C. S.C. and M.Z. gave conceptual advice.
D.L-M recruited the subjects, conducted behavioural experiments and analyzed behavioural data.
D.L-M and NC gathered and analyzed pilot data, designed and performed neuroimaging experiments.
N.C. and F.A. conducted neuroimaging analyses.
S.B. S.C. and M.Z. supervised the project during all its stages.

Abstract

An optimal balance between effective exploitation of available resources and creative exploration of alternatives has been considered as a key to success in many fields. Balancing exploration with exploitation is essential for innovation. A natural instance of innovative decision-making is represented by entrepreneurs, who are considered to excel in identifying new business opportunities, as well as in developing effective implementation strategies. Previous studies have suggested that entrepreneurs exhibit highly adaptive risk-taking behaviour. This finding may be related to a specific pattern of neural activity during explorative choice. Using functional-Magnetic-Resonance-Imaging (*f*MRI), we studied brain activity in a group of innovative entrepreneurs engaged in a classical gambling task, involving exploitative vs. explorative decision-making, and compared them with a matched group of managers. At the behavioural level, entrepreneurs relied more than managers on simple decision-making rules (routines) to decide whether and when to switch from exploitation to exploration. Increased routinization reflected in entrepreneurs activating more than managers brain regions associated with explorative vs. exploitative choice (frontopolar and parietal cortex, locus coeruleus). A superior ability in tracking the evidence in favour of switching to potentially more rewarding options, and disengaging attention from current reassuring ones, may be crucial for the optimal balance of exploration and exploitation exhibited by innovative entrepreneurs. Indeed, activity in the brain regions specifically associated with

explorative choice correlated with the higher level of routinization in their decision-making patterns and overall earnings, and may thus represent the neural signature of their superior ability to innovate.

1. Introduction

The exploration vs. exploitation dilemma (March 1991) has been applied in recent years by the social sciences to the question of how organizations balance the search for radical innovations and the quest for improving existing processes. Social scientists have defined a menu of organizational choices to handle this trade-off, either by separating exploration and exploitation across different units (Benner and Tushman 2003), or by inter-temporally separating cycles of exploration from cycles of exploitation (Burgelman 2002; Siggelkow and Levinthal 2003). However, there is a critical gap at the individual level of analysis: why are some individuals able to seamlessly and appropriately *switch* from exploration to exploitation, balancing both types of behaviours? (Gupta et al. 2006).

This is a fundamental question for social and economic development goals. To contribute to answer it, we aimed to map the neural correlates of explorative and exploitative decision-making, and to unpack differences across groups of individuals. Neuroimaging studies have identified the systems involved in the assessment of reward-related uncertainty (Cohen et al. 2007), in particular the frontopolar cortex (FPC) and locus coeruleus-norepinephrine (LC-NE) system. The former is more active when exploring than when exploiting (Daw et al. 2006). Its activity, in connection with posterior parietal cortex, tracks the relative advantage of switching to foregone options (Boorman et al. 2009b). This process is likely to involve also the LC-NE system, which has been proposed as the structure supporting the attentional switches required to highlight the value of alternative choices (Aston-Jones and Cohen 2005). The LC, indeed, has been shown to switch during behavioural tasks between two modes: phasic (burst activity), associated with fast and accurate performance in responding to targets, and tonic (higher baseline activity), associated with distributed attention favouring exploration (Aston-Jones and Cohen 2005).

Entrepreneurs are an ideal population for studying how exploration and exploitation are balanced, as they need to combine creativity with the effort necessary to turn ideas into marketable products. Neurocognitive studies have so far focused on the explorative side of entrepreneurs, who identify opportunities through highly adaptive risk-taking behaviour (Baron 2004; Gaglio and Katz 2001) and show increased risk-taking performance in gambling tasks, associated with high scores on personality measures of impulsiveness (Lawrence et al. 2008). These findings suggest that entrepreneurs may exhibit differences in neural activity on the explorative end of the exploration-exploitation continuum, but do not address the question of their alleged superiority in switching between exploration and exploitation.

To address this issue, we collected behavioural, cognitive and functional-Magnetic-Resonance-Imaging (*f*MRI) data on 25 innovative entrepreneurs and 28 managers matched for age, education and years of experience. The two groups played a 4-armed bandit task, a classical task of exploitative/explorative decision-making (Lawrence et al. 2008) (Fig. 1, see Supplementary Methods). Briefly, subjects repeatedly selected one of four slot-machines across 300 trials. The slots paid off points noisily around four different means. Payoffs changed from trial to trial, with subjects finding information about the current worth of a slot only through active sampling. The task thus allows to study brain-activity while making exploitative (choosing the same slot as in the previous trial) and explorative (choosing a different slot from the one chosen in the previous trial) decisions.

2. Results

Entrepreneurs did not make explorative decisions more frequently than managers, but they performed marginally better in terms of payoff, showing more timely switches between the two decisional modes (Table 1). These non statistically significant results are in line with previous data (2008), reporting higher quality decision-making in entrepreneurs.

We employed event-related *f*MRI analyses to look for differences in neural activation while entrepreneurs and managers made exploitative vs. explorative choices. First, we assessed brain regions specifically subserving exploitative and explorative decision-making *per se*, independent of group. Compared with explorative choices, exploitative ones elicited significantly stronger activations of dopaminergic mesocortico-limbic regions associated with reward anticipation (Tobler et al. 2007) (Fig. 2, Supplementary Table A; Extended materials tables 1, 4). In particular, the conjoint involvement of the ventromedial prefrontal cortex and the hippocampus supports the role of the former in encoding the value of the current decision while a new choice is made (Boorman et al. 2009b; Daw et al. 2006; Schott et al. 2008).

In contrast, explorative decision-making elicited significantly stronger activations of bilateral frontopolar and posterior parietal regions, as well as anterior insula and locus coeruleus (Fig. 2, Supplementary Table A, Extended materials tables 2, 4, 5). These regions had been previously associated with explorative switching in the context of decision-making (Boorman et al. 2009b; Daw et al. 2006). The continuous tracking of the value of alternative choices, and the intermittent switching to them, may require an increased tonic discharge of the locus coeruleus (Aston-Jones and Cohen 2005). The increase of fronto-parietal activity, combined with higher activation of the LC presumably resulting from prefrontal input (Frank et al. 2009), may then be responsible for explorative switching (Posner and Rothbart 2007). Additionally, exploring entails an assessment of uncertainty and risk, evoking negative bodily states (Craig 2002) mediated by the anterior insula (Bossaerts 2010).

Inter-individual differences in the level of FPC activation have been shown to predict effective behavioural switching to alternative choices (Boorman et al. 2009b). This observation suggests a possible neural basis for an individual disposition towards innovation. Explorative choice in entrepreneurs may then represent a direct test of this hypothesis. We used an exclusive-masking procedure (see Supplementary Methods) to isolate the brain regions that were specifically more activated in entrepreneurs, relative to managers, for the contrast of exploration vs. exploitation. Compared with managers, entrepreneurs showed significantly stronger bilateral activation within the frontopolar and parietal areas associated with the exploration vs. exploitation contrast *per se*, and in the LC (Fig. 3, Supplementary Table A; Extended materials tables 3, 4, 5). Importantly, the evaluation of Blood-Oxygen-Level-Dependent responses in the brainstem suffers from intrinsic limitations (Astafiev et al. 2010). Thus, the involvement of the LC in the exploration vs. exploitation contrast *per se* , as well as, specifically, in explorative choice in entrepreneurs, was also assessed in regions of interest defined with both functional (Minzenberg et al. 2008) and anatomical (Astafiev et al. 2010; Keren et al. 2009a; Keren et al. 2009b) criteria independent of our results (Extended materials table 5). Based on the aforementioned model of the fronto-parietal-LC system subserving exploration, its stronger activation in entrepreneurs (compared with managers) during explorative (compared with exploitative) choice may then represent the neural signature of their superior ability to attend to environmental opportunities, and accumulate evidence to decide when to disengage from exploitation and explore novel alternatives. Indeed, entrepreneurs were significantly faster than managers in making their choices and thus in experimenting novel solutions (Table 1). In agreement with response-time measures, in post-scanning interviews entrepreneurs reported a significantly higher use of routinized procedures to decide whether and when to switch, consistently relying on simple rules (Davis et al. 2009) to choose the next slot machine (i.e. explore). The increased fronto-parietal activity specifically associated with explorative choice in entrepreneurs may then reflect their heightened level of routinization. This hypothesis was confirmed by correlation analyses among individual level of performance (overall earning), routinization (average response-time), and level of activation in "explorative" brain regions (bilateral frontopolar and parietal cortex, and locus coeruleus). First, routinization and performance were significantly related with each other (the shorter the response-time, the higher the payoff) both in the whole sample (correlation = -0.482, p-value = 0.0001) and in entrepreneurs only (correlation = -0.623, p-value = 0.001). Second, the difference between activity associated with exploration and activity associated with exploitation in the "explorative" brain regions was positively correlated with overall earning in both groups (Table 1). Finally, such difference was significantly correlated with routinization only in entrepreneurs. That is, only in entrepreneurs higher activity in these brain regions while exploring, than while exploiting, is associated with *both* higher routinization and better performance.

3. Conclusions

This result is intriguing, since a higher tendency to routinize exploration may appear at odds with innovativeness. Our results rather suggest that innovation success may be enhanced by simple rules, which support the individuals' ability in tracking the evidence in favour of switching to foregone alternatives, and in disengaging attention from current reassuring options, both mechanisms leading to more efficient decisional switching patterns. This evidence might also help explain how to reconcile seemingly contradictory dispositional traits. Similarly to Lawrence et al. (Lawrence et al. 2008), when we assessed subjects' personality traits (Cloninger 1994) we found that, compared with managers, entrepreneurs showed a trend towards higher novelty seeking and significantly lower harm avoidance (related to exploration) but also significantly higher persistence (related to exploitation) (Table 1).

The present results raise a crucial question that awaits supporting empirical evidence. Are cross-group differences in neural activation and routine efficiency the consequence of a self-selection process leading to a career path in line with a natural predisposition, or rather of brain plasticity phenomena consequent from daily work challenges? This is a crucial topic for future investigation. The extent to which entrepreneurial abilities to switch from exploitation to exploration and back can be developed via specific training and practice has significant implications for the enhancement of innovation outcomes and overall competitiveness at the organization as well as at the national and regional system levels.

4. Methods

53 right-handed subjects, without prior neurological or psychiatric illness, participated in the task. All gave informed consent to the study, which was approved by the local ethics committee. Based on their expertise, they were assigned to one of two groups: 25 “entrepreneurs” i.e. who have founded and currently manage their start-up company (4 females) and 28 “managers”, matched for age, education and years of experience, but with no venture-creation experience (7 females). The two groups played the same four-armed bandit task of exploitative vs. explorative decision-making as in Daw et al. (2006). Subjects underwent a training-session before scanning, and were informed that they would be paid based on their overall earning. In each of 300 trials (subdivided in 4 *f*MRI runs), subjects selected one of four slot-machines and received a reward based on a payoff distribution function perturbed by

noise (Fig. 1). Payoffs changed across trials, with subjects finding information about the current worth of a slot-machine only through active sampling. This feature of the task allowed us to study brain-activity while making real explorative/exploitative decisions under uniform conditions.

In a post-scanning interview, subjects reported their choice strategies. This information was used to construct a measure of routinization extent (see Supplementary Methods).

Single-subject event-related *f*MRI responses were modelled at the midway point between slots presentation and subjects' response, separately for exploitative (same slot as in the previous trial) and explorative (different slot than in the previous trial) choices. Random-effect group analyses were computed with a 2 x 2 [(choice: exploitative/explorative) x (group: entrepreneurs/managers)] full factorial design. Unless otherwise stated, the statistical threshold was $p<0.05$, corrected for multiple comparisons using both Family-Wise-Error (FWE) at the single-voxel level and cluster-extent. Correlations among individual level of activation in regions showing specific effects for explorative choice in entrepreneurs, performance, and routinization were also investigated.

5. Figures and Tables

Table 1: Personality, decision-making and routinization performance, and brain activation.

Personality test - Temperament and Character - TCI 56 (1=low - 5=high; average scores)	Managers	Entrepreneurs	p-value (F-test)	n*
Temperament				
Harm Avoidance	2.88	2.08	0.000	38
Novelty Seeking	3.01	3.18	0,075*	38
Reward Dependence	3.47	3.44	0.891	38
Persistence	3.61	3.95	0.055	38
Character				
Self-Directedness	3.88	4.03	0.306	38
Cooperativeness	3.85	3.68	0.442	38
Self-Trascendence	2.67	2.94	0.318	38

Behavioral decision making performance (average scores over 300 trials)	Managers	Entrepreneurs	p-value (F-test)	n
Number of explorative choices	144	136	0.571	53
Number of exploitative choices	150	159	0.521	53
Cumulative profit (in euros)	42.04	42.84	0.166	53

Routinization (average scores over 300 trials)	Managers	Entrepreneurs	p-value (F-test)	n**
Response time (in seconds)	0.45	0.39	0.003	46
Extent of routinization (0=random decision - 4=max routinization)	1.83	2.48	0.030	46

Response time and brain activation (exploration minus exploitation)	Entrepreneurs (n = 25)		All subjects (n = 53)	
	Correlation	p-value	Correlation	p-value
left fronto polar cortex (lFPC)	-0.430	0.036	-0.257	0.069
right fronto polar cortex (rFPC)	-0.544	0.006	0.030	0.834
left posterior parietal cortex (lPPC)	-0.313	0.136	-0.107	0.454
right posterior parietal cortex (rPPC)	-0.544	0.005	0.003	0.981
Locus coeruleus (LC)	-0.496	0.014	-0.134	0.350

Performance and brain activation (exploration minus exploitation)	Entrepreneurs (n = 25)		All subjects (n = 53)	
	Correlation	p-value	Correlation	p-value
left fronto polar cortex (lFPC)	0.520	0.009	0.317	0.022
right fronto polar cortex (rFPC)	0.644	0.001	0.314	0.023
left posterior parietal cortex (lPPC)	0.522	0.008	0.354	0.010
right posterior parietal cortex (rPPC)	0.671	0.000	0.340	0.010
Locus coeruleus (LC)	0.505	0.012	0.366	0.008

* Due to a-priori hypotheses (Lawrence et al. 2008, reference number 12), the significance level for the Novelty Seeking trait is reported as a one-tailed test. All the other significance levels report two-tailed p-values.

n* = 23 managers and 15 entrepreneurs
n ** = 23 managers and 23 entrepreneurs

Figures

Figure 1. 4-armed bandit task
Graphical representation of the 4-armed bandit task and of the slots’ payoff functions (following the task design of Daw et al. 2006).

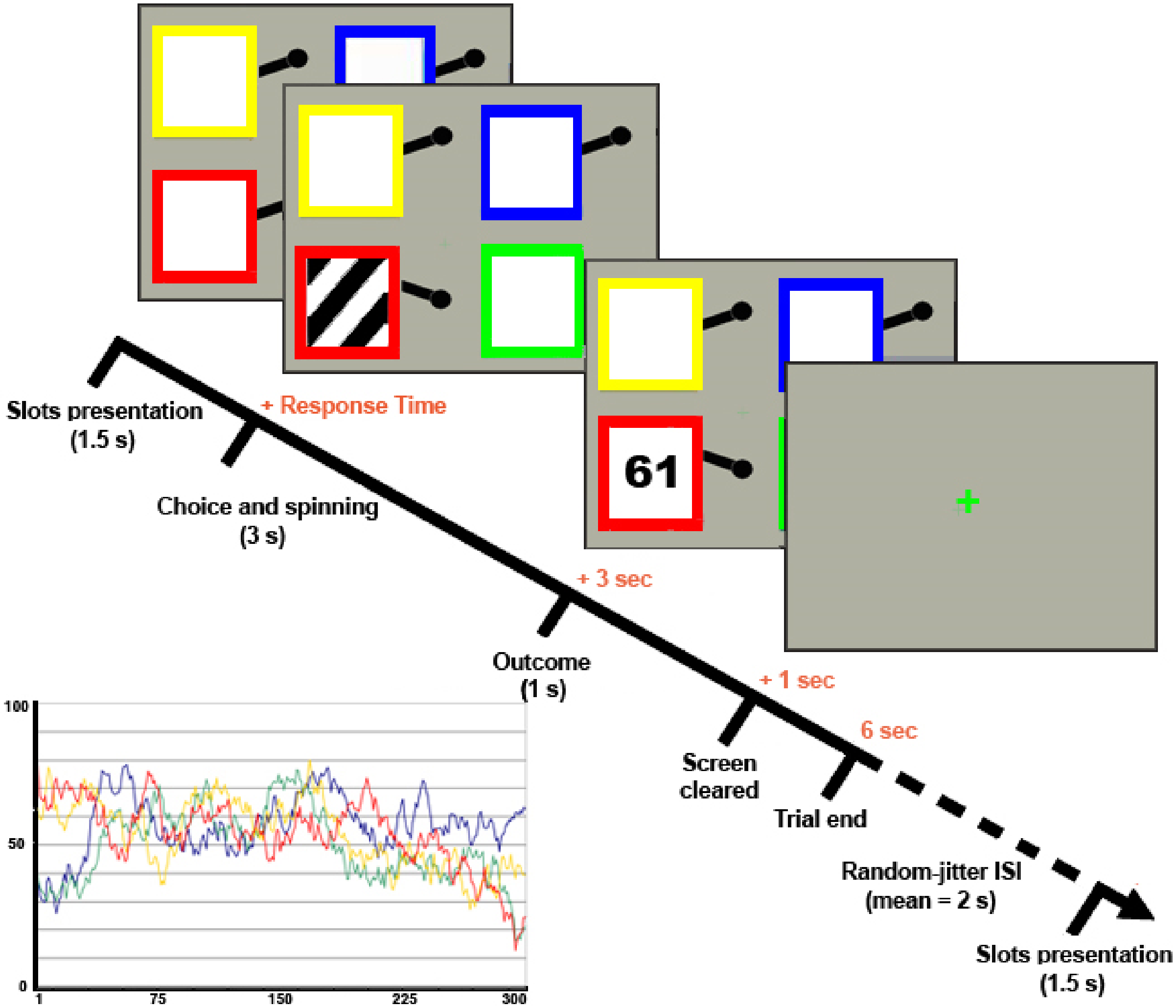


Figure 2. Cerebral regions more strongly activated during explorative and exploitative choices

Cerebral regions more strongly activated by exploitative than explorative choices (left), and by explorative than exploitative choices (right).

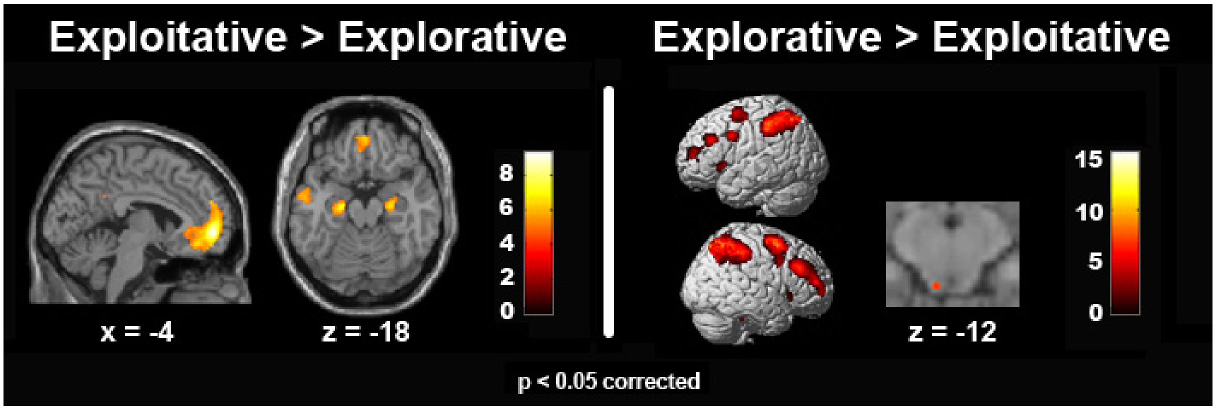
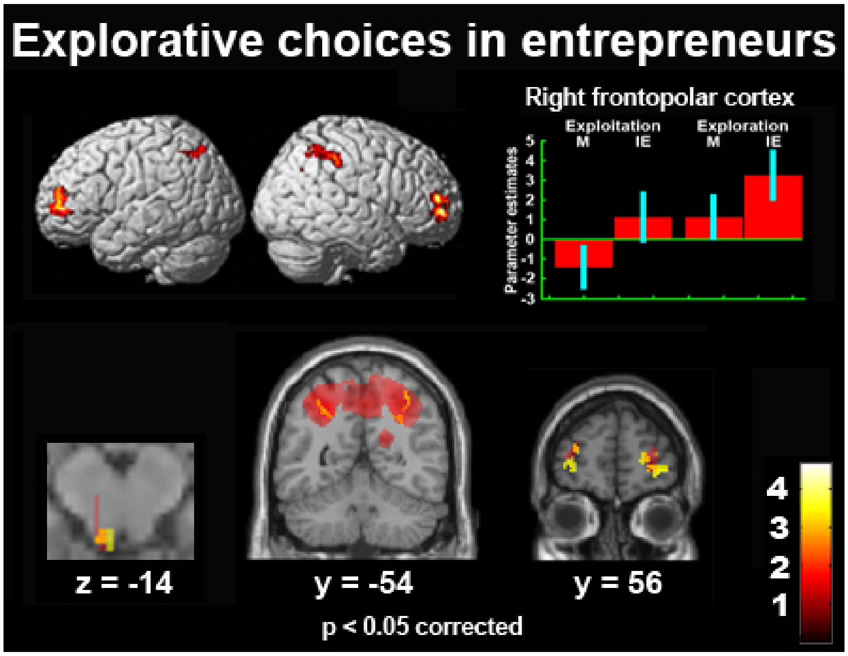


Figure 3. Cerebral regions more strongly activated by explorative choices in innovative entrepreneurs.

The regions specifically associated with explorative choice in innovative entrepreneurs are shown in the 3D-renders at the top of the figure. In the sections at the bottom, these regions (yellow) are superimposed on those more strongly activated by explorative than exploitative decision-making *per se* (red). The reported regions survive a $p<0.05$ correction (whole-brain or small-volume) for multiple comparisons. The histogram represents mean (± standard error) for parameter estimates at the peak of right FPC cortex activation (34, 56, -4), for exploitative and explorative choices in managers (M) and innovative entrepreneurs (IE), showing a specific effect of explorative choice in innovative entrepreneurs. For graphical purposes, the activations of the locus coeruleus in innovative entrepreneurs (-2, -32, -14) is shown at $p<0.005$ uncorrected.



6. **Supplementary Methods**

Subjects

53 right-handed subjects (11 females), with normal or corrected-to-normal visual acuity and without a prior history of neurological or psychiatric illness, participated in the task. Based on their expertise, they were assigned to one of two groups: 25 “entrepreneurs” (4 females) and 28 “managers” (7 females). All gave informed consent to the study, which was approved by the local ethics committee.

4-armed bandit task and routinization measure

Subjects performed a “4-armed bandit task” that has been already used in neuroimaging studies on the neural bases of explorative vs. exploitative choice (Figure 1). Task-design and payoff-structure were the same as in Daw et al. (Daw et al. 2006) study, with 300 trials overall, subdivided in 4 *f*MRI runs each comprising 75 trials. Subjects underwent a training session preceding the functional acquisition and were informed that they would be paid based on their overall earning in the study. Additionally, they were asked to report their choice strategies about the 4-armed bandit task in a post-scanning interview. This information served to construct a measure of routinization extent. This index captures the extent to which the description of the procedure the participant used to play the gambling task follows previously recognized features of field-observed routines. Namely we asked subjects: ‘Please describe the general strategy you followed while playing’. Previous literature has characterized routines in terms of: repeated action sequences, reliability, occasional suboptimality, and increased speed (Cohen and Bacdayan

1994). For 7 subjects (5 managers, 2 entrepreneurs), due to technical problems with the transcript, it was not possible to analyze the information of the post-scanning interview. For all the other 46 subjects (23 managers and 23 entrepreneurs) we counted how many of these 4 features appeared in the description of the strategy followed to play, thus generating a measure of routinization extent ranging from 0 to 4.

Images acquisition

Anatomical T1-weighted and functional T2*-weighted MR images were acquired with a 3 Tesla Philips Achieva scanner, using an 8-channels Sense head coil (Sense reduction factor=2). 307 images per run were acquired using a T2*-weighted gradient-echo, echo-planar pulse sequence (37 ascending transverse slices covering the whole brain except for occipital regions in some subjects, tilted 30° downward with respect to the bi-commissural line, TR=2000 ms, TE=30 ms, flip-angle=85 degrees, FOV=192 mm x 192 mm, slice-thickness=3.4 mm, inter-slice gap=0.2, in-plane resolution=3 mm x 3 mm).

Data processing and analyses

Image pre-processing (artifact-repair, realign-and-unwarp, slice-timing, spatial normalization and smoothing) and statistical analysis were performed using SPM8 and Matlab v7.4 (Worsley and Friston 1995). In the statistical analysis we focused on the regions showing significant changes in cerebral activity related to exploitative vs. explorative decision-making. Single-subject event-related *f*MRI responses were modelled as delta functions at the midway point between slots presentation and subjects’ response, separated for exploitative (same slot as in the previous trial) and explorative (different slot than in the previous trial) choices. Random-effect group analyses were computed by means of a 2 x 2 [(choice: exploitative vs. explorative) x (group: entrepreneurs vs. managers)] full factorial design with sphericity-correction for repeated measures (Friston et al. 2002). We investigated the main effect of choice type (exploitative vs. explorative) and group (entrepreneurs vs. managers) and, using exclusive-masking (mask threshold=0.005), the regions that were specifically associated with explorative choices in entrepreneurs (Extended materials tables 3, 4, 5).

Statistical maps were thresholded at $p<0.05$ corrected for multiple comparisons using both Family-Wise-Error (FWE) at the single-voxel level and cluster-extent.

Based on a-priori hypotheses concerning the involvement of the locus coeruleus in explorative vs. exploitative choice, as well as in explorative choice by entrepreneurs, we employed a small-volume correction (Worsley et al. 1996) on the related statistical maps. This procedure was applied to 8-mm-radius spheres centered on the coordinates reported in previous *f*MRI (Minzenberg et al. 2008) and anatomical *in-vivo* mapping((Keren et al. 2009a; Keren et al. 2009b)p.1264; (Eickhoff et al. 2005)) studies of the locus coeruleus (Extended materials table 5). For the same reason, locus coeruleus activity was examined, in the statistical map of explorative choices in entrepreneurs, also at a lenient threshold of $p<0.005$ uncorrected for multiple comparisons. Additionally, we aimed to directly compare brain activations in our study with those associated with tracking the value of current versus alternative choices by Boorman et al (Boorman et al. 2009b). To this purpose, the same SVC procedure, based on the coordinates reported in their study, was applied on the “exploit vs. explore”, “explore vs. exploit” and “explorative choice in entrepreneurs” statistical maps (Extended materials table 4). Finally, for all subjects we assessed correlations among individual level of performance (overall points accumulated in the gambling task), routinization (average response-time), and level of activation (mean parameter estimates averaged over voxels in the whole cluster) in brain regions showing specific effects for explorative choice in entrepreneurs (bilateral frontopolar and parietal cortex, and locus coeruleus).

Supplementary table A. Neural correlates of exploitative vs. explorative choice, and explorative choice in entrepreneurs

K	H	Anatomical region (BA/region)	ATp		MNI		Voxel T-score	Cluster p-value
				x	y	z		
		Exploit > Explore						
1815	L	Mid orbital gyrus		-4	54	-4	**9.35**	**0.000**
71	L	IFG pars orbitalis		-36	34	-12	**6.92**	**0.000**
69	L	IFG pars triangularis (45*)	60	-50	30	6	**6.51**	**0.000**
4	R	SMA (6)	50	8	-20	54	**4.96**	**0.017**
34	R	Rolandic operculum (OP4*)	30	56	2	4	**5.52**	**0.001**
2	L	Rolandic operculum (IPC PFcm*)	70	-42	-34	20	**5.08**	**0.026**
3	L	Postcentral gyrus (OP4*)	20	-60	-2	16	**5.04**	**0.021**
17	L	Posterior cingulate cortex		-6	-48	30	**5.48**	**0.003**
213	L	Middle temporal gyrus		-58	-4	-20	**6.39**	**0.000**
42	L	Middle temporal gyrus		-58	-40	0	**5.63**	**0.000**
167	L	Hippocampus (CA/SUB)	80/50	-22	-16	-18	**7.09**	**0.000**
131	R	Hippocampus (CA)	50	24	-16	-16	**6.91**	**0.000**
		Explore > Exploit						
771	L	Superior frontal gyrus		-24	-4	52	**10.81**	**0.000**
468	L	Middle frontal gyrus		-42	28	30	**7.25**	**0.000**
274	L	Precentral gyrus		-48	6	34	**7.83**	**0.000**
1565	R	Superior frontal gyrus		24	-2	54	**12.50**	**0.000**
1185	R	Middle frontal gyrus		36	40	32	**7.78**	**0.000**
199	L	Insula lobe		-36	18	0	**6.74**	**0.000**
114	R	Insula lobe		34	22	0	**6.07**	**0.000**
8239	L	Superior parietal lobule (SPL 7A*)	80	-16	-68	56	**15.64**	**0.000**

	R	Superior parietal lobule (SPL 7A*)	50	20	-66	56	**14.23**	
	L	Inferior parietal lobule (hIP3*)	40	-28	-56	46	**13.98**	
	R	Inferior parietal lobule (hIP1*)	30	34	-44	42	**12.97**	
181	L	SMA		-4	10	50	**6.91**	**0.000**
36	R	Cerebellum (VI*)	63	34	-36	-32	**6.19**	**0.000**
5	L	Locus coeruleus		-10	-32	-24	**5.17**	**0.015**
2	L	Locus coeruleus		-4	-32	-12	**5.05**	**0.026**
		<u>Explorative choice in entrepreneurs</u>						
345	L	Middle frontal gyrus		-28	50	12	4.67	**0.001**
	L	Superior frontal gyrus		-32	56	0	4.01	
16	L	Precentral gyrus		-50	0	28	3.83	
256	R	Middle orbital gyrus		34	56	-4	4.52	**0.006**
	R	Superior frontal gyrus		22	58	10	3.99	
135	R	Middle frontal gyrus		42	30	40	3.93	
159	L	Inferior parietal lobule (hIP3*)	30	-28	-54	44	**4.92**	**0.043**
328	R	Superior parietal lobule		26	-48	42	**4.87**	**0.002**
	R	Inferior parietal lobule (hIP3*)	40	34	-48	52	4.46	
33	R	Superior parietal lobule (SPL 7P*)	20	18	-60	50	4.00	
	R	Precuneus (SPL 7P)	80	14	-70	60	3.77	
27	R	Cerebellum		20	-38	-30	3.89	
	R	Cerebellum		24	-38	-34	3.71	
72	R	Thalamus		14	-22	12	4.22	
21	R	Putamen		28	-6	2	3.87	
10	R	Putamen		30	-16	0	3.68	
10		Locus coeruleus		-2	-32	-14	2.98**	
53		Locus coeruleus		-12	-34	-24	3.49**	

Supplementary table A. From left to right, the extent of the cluster in number of voxels (K; 2 x 2 x 2 mm^3), the hemispheric lateralization (H; L = Left, R = Right), the estimated anatomical region, and Brodmann Area (BA) where available in the Anatomy Toolbox (Eickhoff et al. 2005), its probabilistic localization (ATp; asterisks denote assignment by the Anatomy Toolbox), the stereotactic coordinates, the local-maxima T-score and the cluster p-value, are reported for the regions that were more strongly activated by exploitative than explorative decision-making (top), explorative than exploitative decision-making (middle), and explorative decision-making in entrepreneurs (bottom). Values shown in the Cluster p-value column, and those shown in bold font in the T-score column, survive a statistical threshold of $p < 0.05$ corrected for multiple comparisons.

IFG = Inferior Frontal Gyrus, SMA = Supplementary Motor Area, OP = Parietal Operculum, IPC = Inferior Parietal Cortex, CA = Cornu Ammonis, SUB = Subiculum, SPL = Superior Parietal Lobule, hIP = human IntraParietal, **$p < 0.005$ uncorrected for multiple comparisons due to a-priori hypotheses.

7. Extended Material and Methods

*f*MRI Subjects

53 right-handed (Oldfield 1971) healthy subjects (11 females; females' mean age =33.333 years, standard deviation [s.d.]=6.020; males' mean age =35.595 years, s.d.=6.911) participated in the study. Based on their expertise, they were assigned to 2 groups: 25 "entrepreneurs" (mean age= 35.160 years, s.d.=6.555; 4 females) and 28 "managers" (mean age= 35.036 years, s.d.=7.131; 7 females). All subjects had normal or corrected-to-normal visual acuity. All reported no history of psychiatric or neurological disorders and no current use of psychoactive medications. They gave their written informed consent to the experimental procedure, which was approved by the local Ethics Committee.

*f*MRI Task and Experimental procedure

Subjects performed a classic "4-armed bandit task" that has been already used in neuroimaging studies on the neural bases of explorative vs. exploitative choice (Daw et al. 2006). The task involved repeated choices among four differently colored slot machines that lead to variable gains in successive trials all having the same structure (Figure 1). The slots were shown for 1.5 seconds, during which subjects had to indicate the chosen one by pressing the corresponding button of a response box with the right hand. Responses given within this period started the animation of the slot machine (e.g., rotation of the spinning reels for 3 sec), after which the payoff was shown for 1 sec. If no choice was given within the slots-presentation period, a red X was displayed for 4.2 sec., and a new trial was started. The trial sequence lasted 6 seconds and was followed by a green “+”during the InterStimulus Interval (ISI). The duration of the latter was varied (“jittered”) in every trial in order to desynchronize the timings of event-types with respect to the acquisition of single slices within functional volumes and to optimize statistical efficiency (Dale 1999). The OptSeq2 Toolbox (http://surfer.nmr.mgh.harvard.edu/optseq/) was used to estimate the optimal ISIs (mean ISI=2 sec, s.d.=1.987 sec, minimum=0 sec; maximum=10 sec). Subjects played 300 trials overall, subdivided in 4 *f*MRI-runs of 75 trials each. The payoff structure was the same as in Daw et al. (Daw et al. 2006). Namely, the payoff for choosing the *i*th slot machine on trial *t* was between 1 and 100 points, drawn from a Gaussian distribution (standard deviation $\sigma o = 4$) around a mean $\mu i,t$ and rounded to the nearest integer. At each time-step, the means diffused in a decaying Gaussian random walk, with $\mu i,t+1 = \lambda \mu i,t + (1 - \lambda)\theta + v$ for each *i*. The decay parameter λ was 0.9836, the decay center θ was 50, and the diffusion noise v was zero-mean Gaussian with standard deviation σd = 2.8 (Figure 1 for a graphical representation of the payoffs of the 4 slots in all the 300 trials).

Visual stimuli were viewed via a back-projection screen located in front of the scanner and a mirror placed on the head-coil. The software Presentation 14.4 (Neurobehavioral systems, Albany, CA, http://www.neurobs.com) was used both for stimulus presentation and subjects’ answers recording. All subjects underwent a training session preceding the functional acquisition and were informed that they would be paid based on their overall earning in the whole study. Additionally, they were asked to report their choice strategies in a post-scanning interview.

*f*MRI-data acquisition

Anatomical T1-weighted and functional T2*-weighted MR images were acquired with a 3 Tesla Philips Achieva scanner (Philips Medical Systems, Best, NL), using an 8-channels Sense head coil (sense reduction factor=2). Functional images (307 per run) were acquired using a T2*-weighted gradient-echo, echo-planar (EPI) pulse sequence (37 ascending transverse slices covering the whole brain except for posterior occipital regions in some subjects, tilted 30° downward with respect to the bi-commissural line to reduce susceptibility artifacts in orbitofrontal regions, TR=2000 ms, TE=30 ms, flip-angle=85 degrees, FOV=192 mm x 192 mm, slice-thickness=3.4 mm, inter-slice gap=0.2, in-plane resolution=3 mm x 3 mm). Immediately after the functional scanning, a high-resolution T1-weighted anatomical scan (150 slices, TR=600 ms, TE=20 ms, slice-thickness=1 mm, in-plane resolution=1 mm x 1 mm) was acquired for each subject.

*f*MRI-data pre-processing and statistical analysis

Image pre-processing and statistical analysis were performed using SPM8 (Wellcome Department of Cognitive Neurology, http://www.fil.ion.ucl.ac.uk/spm), implemented in Matlab v7.4 (Mathworks, Inc., Sherborn, MA) (Worsley and Friston 1995). The first 5 volumes of each subject were discarded to allow for T1 equilibration effects. All 1228 volumes from each subject underwent an initial quality-check step using the Artifact repair toolbox (http://spnl.stanford.edu/tools/ArtRepair/ArtRepair.htm), by means of which artifacts between the slices within a volume were detected and repaired by interpolation. All volumes were then spatially realigned (Friston et al. 1996) to the first volume of the first run to correct for between-scan motion, and unwarped (Andersson et al. 2001). A mean-image from the realigned volumes was created that was segmented in grey matter, white matter, cerebrospinal fluid (CSF), bone, soft tissues and background (air) using the “new” unified segmentation implemented in SPM8. During the segmentation the gray-matter component is automatically normalized to a grey-matter probabilistic map (http://Loni.ucla.edu/ICBM/ICBM_TissueProb.html). The derived spatial transformations were then applied to the realigned-and-unwarped T2*-weighted volumes, which were resampled in 2 x 2 x 2-mm voxels after normalization. All functional volumes were then spatially smoothed with an 8-mm full-width half-maximum (FWHM) isotropic Gaussian kernel to compensate for residual between-subject variability after spatial normalization. The smoothed volumes underwent a further quality check using the Artifact-Repair Toolbox to detect and repair trough interpolation, the volumes characterized by a) excessive variance in global intensity with respect to the mean of the run or b) rapid movement of the head. The thereby-obtained volumes were then globally scaled to 100. The resulting time series across each voxel were then high-pass filtered to 1/128 Hz, and serial autocorrelations were modelled as an AR(1) process.

In the statistical analysis we focused on the regions showing significant changes in cerebral activity related to exploitative vs. explorative decision-making. Statistical parametric maps were generated using a random-effect model, implemented in a 2-levels procedure (Friston et al. 1999). At the first (single-subject) level, event-related *f*MRI responses were modelled as delta ‘‘stick’’ functions by a design matrix comprising the midway point between slots presentation and subjects’ response, separately for exploitative (same slot as in the previous trial) and explorative (different slot than in the previous trial) choices. Regressors modelling events were convolved with a canonical hemodynamic response function (HRF), along with its temporal and dispersion derivatives, and parameter estimates for all regressors were obtained by maximum-likelihood estimation. At the second level, random-effect group analyses (Friston et al. 1999) were computed by means of a 2 x 2 [(choice: exploitative vs. explorative) x (group: entrepreneurs vs. managers)] full-factorial design with sphericity-correction for repeated measures (Friston et al. 2002). Several analyses were run. First, we investigated the main effect of choice type (exploitative vs. explorative) and group (entrepreneurs vs. managers) (see Extended materials tables 1,2). Then we turned to the regions showing specific choice- and group-effects to investigate the regions that were specifically associated with only one of the four sub-conditions of interest. To this purpose we used an exclusive-masking procedure, in which the sub-condition of interest was masked (at $p<0.005$ uncorrected) by the disjunction of the other three variables (e.g., explorative-entrepreneurs exclusively masked by explorative-managers, exploitative-entrepreneurs and exploitative-managers) (see Extended materials table 3). We chose an exclusive-mask at the lenient threshold of 0.005 uncorrected so that more activity than in the single-condition analysis was granted to non-interest conditions, to highlight the specificity of voxels that were activated by only one given sub-condition. Statistical maps were thresholded at $p<0.05$ corrected for multiple comparisons using both Family-Wise-Error (FWE) at the single-voxel level and cluster-extent. Based on a-priori hypotheses concerning the involvement of the locus coeruleus in explorative decision-making by entrepreneurs, we employed a small-volume correction (Worsley et al. 1996) on the related statistical map. This procedure was applied to 8-mm-radius spheres centred on the coordinates reported in previous *f*MRI (Minzenberg et al. 2008) and anatomical *in-vivo* mapping ((Keren et al. 2009a), p.1264, (Astafiev et al. 2010)) studies of the locus coeruleus (see Extended materials table 5). In addition, only for explorative purposes we examined specific effects in this statistical map of explorative choices in entrepreneurs on locus coeruleus activity at a lenient threshold of $p<0.005$ uncorrected for multiple comparisons. Finally, a small-volume correction was also applied to the coordinates reported by a recent paper investigating the role of the frontopolar and parietal cortex in tracking the value of alternative courses of action and switching to them (i.e. exploring) (Boorman et al. 2009a) (see Extended materials table 4)

The location of the activation foci was determined in the stereotactic space of Talairach and Tournoux (Talairach and Tournoux 1988) after correcting for differences between the latter and the MNI coordinate systems by means of a nonlinear transformation (see http://www.mrc-cbu.cam.ac.uk/Imaging/Common/mnispace.shtml). Those cerebral regions for which maps are provided were also localized with reference to cytoarchitectonical probabilistic maps of the human brain, using the SPM-Anatomy toolbox v1.7b (Eickhoff et al. 2005).

Extended materials

Table 1. Neural correlates of exploitative vs. explorative choice

K	H	Anatomical region (BA/region)	ATp		MNI		Voxel T-score	Cluster p-value
				x	y	z		
		Exploit > Explore						
1815	L	Mid orbital gyrus		-4	54	-4	**9.35**	**0.000**
	L	Medial superior frontal gyrus		-8	54	26	**6.81**	
	R	Medial superior frontal gyrus		8	56	20	**6.70**	
	L	Rectus gyrus (vmPFC)		0	48	-20	**6.43**	
	L/R	ACC/ Mid orbital gyrus		0	42	-2	**6.11**	
	L/R	ACC		-2	38	0	**6.03**	
	L	Superior frontal gyrus		-20	28	44	**5.85**	
71	L	IFG pars orbitalis		-36	34	-12	**6.92**	**0.000**
69	L	IFG pars triangularis (45*)	60	-50	30	6	**6.51**	**0.000**
4	R	SMA (6)	50	8	-20	54	**4.96**	**0.017**
34	R	Rolandic operculum (OP4*)	30	56	2	4	**5.52**	**0.001**
2	L	Rolandic operculum (IPC PFcm*)	70	-42	-34	20	**5.08**	**0.026**
3	L	Postcentral gyrus (OP4*)	20	-60	-2	16	**5.04**	**0.021**
17	L	Posterior cingulate cortex		-6	-48	30	**5.48**	**0.003**
213	L	Middle temporal gyrus		-58	-4	-20	**6.39**	**0.000**
	L	Middle temporal gyrus		-52	4	-28	**5.46**	
	L	Middle/superior temporal gyrus		-52	-12	-10	**5.15**	
42	L	Middle temporal gyrus		-58	-40	0	**5.63**	**0.000**
167	L	Hippocampus (CA/SUB)	80/50	-22	-16	-18	**7.09**	**0.000**
131	R	Hippocampus (CA)	50	24	-16	-16	**6.91**	**0.000**

From left to right, the extent of the cluster in number of voxels (K; 2 x 2 x 2 mm^3), the hemispheric lateralization (H; L = Left, R = Right), the estimated anatomical region, and Brodmann Area (BA) where available in the Anatomy Toolbox (Eickhoff et al. 2005), its probabilistic localization (ATp; asterisks denote assignment by the Anatomy Toolbox), the stereotactic coordinates, the local-maxima T-score and the cluster p-value, are reported for the regions that were more strongly activated by exploitative than explorative decision-making. Values shown in bold font in the T-score or Cluster p-value columns survive a statistical threshold of $p < 0.05$ corrected for multiple comparisons.

vmPFC = ventromedial Prefrontal Cortex, ACC = Anterior Cingulate Gyrus, IFG = Inferior Frontal Gyrus, SMA = Supplementary Motor Area, OP = Parietal Operculum, IPC = Inferior Parietal Cortex, CA = Cornu Ammonis, SUB = Subiculum, FD = Fascia Dentata, LB = Amygdala (LateroBasal group)

Extended materials Table 2. Neural correlates of explorative vs. exploitative choice

K	H	Anatomical region (BA/region)	ATp		MNI		Voxel T-score	Cluster p-value
				x	y	z		
		Explore > Exploit						
771	L	Superior frontal gyrus		-24	-4	52	**10.81**	**0.000**
468	L	Middle frontal gyrus		-42	28	30	**7.25**	**0.000**
	L	Middle frontal gyrus		-34	52	20	**6.18**	
274	L	Precentral gyrus		-48	6	34	**7.83**	**0.000**
1565	R	Superior frontal gyrus		24	-2	54	**12.50**	**0.000**
	R	Precentral gyrus		48	10	38	**5.72**	
	R	Middle frontal gyrus		44	10	40	**5.71**	
1185	R	Middle frontal gyrus		36	40	32	**7.78**	**0.000**
	R	IFG pars triangularis		36	32	26	**7.38**	
	R	Superior frontal gyrus		28	54	10	**6.34**	
199	L	Insula lobe		-36	18	0	**6.74**	**0.000**
114	R	Insula lobe		34	22	0	**6.07**	**0.000**
8239	L	Superior parietal lobule (SPL 7A*)	80	-16	-68	56	**15.64**	**0.000**
	R	Superior parietal lobule (SPL 7A*)	50	20	-66	56	**14.23**	
	R	Precuneus (SPL 7P*)	70	12	-70	58	**14.00**	
	L	Inferior parietal lobule (hIP3*)	40	-28	-56	46	**13.98**	
	R	Inferior parietal lobule (hIP1*)	30	34	-44	42	**12.97**	
	R	Superior occipital gyrus		24	-64	44	**11.84**	
	L	Precuneus		-6	-66	48	**10.71**	
	R	Precuneus		18	-56	24	**8.14**	
181	L	SMA		-4	10	50	**6.91**	**0.000**
	R	SMA		2	10	52	**6.31**	
	R	Middle/Anterior cingulate cortex		8	24	36	**5.38**	
36	R	Cerebellum (VI*)	63	34	-36	-32	**6.19**	**0.000**
5	L	Locus coeruleus		-10	-32	-24	**5.17**	**0.015**
2	L	Locus coeruleus		-4	-32	-12	**5.05**	**0.026**

From left to right, the extent of the cluster in number of voxels (k; 2 x 2 x 2 mm^3), the hemispheric lateralization (H; L = Left, R = Right), the estimated anatomical region and Brodmann Area (BA) where available in the Anatomy Toolbox (Eickhoff et al. 2005), its probabilistic localization (ATp; asterisks denote assignment by the Anatomy Toolbox), the stereotactic coordinates, the local-maxima T-score and the cluster p-value, are reported for the regions that were more strongly activated by explorative than exploitative decision-making. Values shown in bold font in the T-score or Cluster p-value columns survive a statistical threshold of $p < 0.05$ corrected for multiple comparisons.

L = Left, R = Right, IFG = Inferior Frontal Gyrus, SPL = Superior Parietal Lobule, hIP = human IntraParietal, SMA = Supplementary Motor Area

Extended materials Table 3. Neural correlates of explorative choice in entrepreneurs

K	H	Anatomical region (BA/region)	ATp		MNI		Voxel T-score	Cluster p-value
				x	y	z		
		Explorative choice in entrepreneurs						
345	L	Middle frontal gyrus		-28	50	12	4.67	**0.001**
	L	Middle orbital gyrus		-30	48	-2	4.63	
	L	Superior frontal gyrus		-32	56	0	4.01	
16	L	Precentral gyrus		-50	0	28	3.83	
256	R	Middle orbital gyrus		34	56	-4	4.52	**0.006**
	R	Superior frontal gyrus		22	58	10	3.99	
	R	Middle frontal gyrus		32	50	12	3.94	
	R	IFG pars orbitalis		42	46	-2	3.22	
135	R	Middle frontal gyrus		42	30	40	3.93	
	R	IFG pars triangularis		34	32	28	3.79	
159	L	Inferior parietal lobule (hIP3*)	30	-28	-54	44	**4.92**	**0.043**
	L	Superior parietal lobule		-28	-64	48	4.67	
	L	Superior parietal lobule (SPL 7A*)	70	-22	-70	56	4.09	
	L	Superior parietal lobule (SPL 7PC*)	60	-32	-52	50	4.02	
328	R	Superior parietal lobule		26	-48	42	**4.87**	**0.002**
	R	Inferior parietal lobule (hIP3*)	40	34	-48	52	4.46	
	R	Inferior parietal lobule (2*)	40	38	-40	48	4.42	
	R	Supramarginal gyrus (hIP2*)	40	42	-36	40	3.96	
	R	Angular gyrus (hIP3*)	40	32	-58	48	3.9	
	R	Supramarginal gyrus (IPC PFt)	40	48	-32	42	3.54	
33	R	Superior parietal lobule (SPL 7P*)	20	18	-60	50	4.00	
	R	Precuneus (SPL 7P)	80	14	-70	60	3.77	
27	R	Cerebellum		20	-38	-30	3.89	
	R	Cerebellum		24	-38	-34	3.71	
72	R	Thalamus		14	-22	12	4.22	
21	R	Putamen		28	-6	2	3.87	
10	R	Putamen		30	-16	0	3.68	
10		Locus coeruleus		-2	-32	-14	2.98**	
53		Locus coeruleus		-12	-34	-24	3.49**	

From left to right, the extent of the cluster in number of voxels (k; 2 x 2 x 2 mm^3), the hemispheric lateralization (H; L = Left, R = Right), the estimated anatomical region and Brodmann Area (BA) where available in the Anatomy Toolbox (Eickhoff et al. 2005), its probabilistic localization (ATp; asterisks denote assignment by the Anatomy Toolbox), the stereotactic coordinates, the local-maxima T-score and the cluster p-value, are reported for the regions that were specifically associated with explorative decision-making in the entrepreneurs group. Values shown in the Cluster p-value column, and those shown in bold font in the T-score column, survive a statistical threshold of $p < 0.05$ corrected for multiple comparisons.

L = Left, R = Right, IFG = Inferior Frontal Gyrus, hIP = human IntraParietal, SPL = Superior Parietal Lobule, IPC = Inferior Parietal Cortex. **$p < 0.005$ uncorrected for multiple comparisons, for explorative purposes due to a-priori hypotheses.

Extended materials Table 4. Small-volume-correction in Boorman's et al (2009) coordinates

x	y	z	Region	Proposed role	SVC p-value Exploit>Explore	SVC p-value Explore>Exploit	SVC p-value Explorative choice in entrepreneurs
-34	56	-8	L PFC	Tracking value of alternative choice	0.673	**0.002**	**0.008**
36	54	0	R PFC	Tracking value of alternative choice	0.631	**0.000**	**0.001**
-32	-60	52	L IPS	Tracking value of alternative choice	nsc	**0.000**	**0.000**
50	-46	46	R IPS	Tracking value of alternative choice	0.614	**0.000**	0.066
48	-42	44	R IPS	Fronto-parietal connectivity increase leading to switch	0.632	**0.000**	**0.008**
-6	48	-8	vmPFC	Tracking value of current choice	**0.000**	nsc	0.679

We aimed to directly compare brain activations in our study with those associated with tracking the value of current versus alternative choices by Boorman et al (Boorman et al. 2009a). To this purpose, the same Small volume correction in the frontopolar, parietal and ventromedial prefrontal coordinates reported in the *f*MRI study by Boorman et al. (Boorman et al. 2009a), applied to 8-mm-radius spheres in the statistical maps of "exploit vs. explore", "explore vs. exploit" and "explorative choice in entrepreneurs". Values shown in bold font survive a statistical threshold of p < 0.05 FWE corrected for multiple comparisons.

SVC = Small-Volume-Correction, L = Left, R = Right, PFC = Prefrontal Cortex, IPS = IntraParietal Sulcus, vmPFC = ventromedial Prefrontal Cortex, nsc = No suprathreshold clusters.

Extended materials Table 5. Explorative choice *per se* and in entrepreneurs: Small-volume-correction in anatomically independent Locus Coeruleus coordinates

x	y	z	Paper	SVC p-value Exploit vs. explore	SVC p-value Explore vs. exploit	SVC p-value Explorative choice in entrepreneurs
-3	-38	-25	Astafiev et al 2010	nsc	**0.024**	**0.050**
5	-38	-25	Astafiev et al 2010	nsc	**0.012**	0.065
8	-40	-15	Minzenberg et al 2008	nsc	**0.006**	**0.032**
-4	-35	-12	Minzenberg et al 2008	nsc	**0.002**	0.060
-2	-36	-18	Keren et al 2009	nsc	**0.004**	0.060
-3	-37	-21	Keren et al 2009	nsc	**0.007**	**0.043**
-4	-37	-24	Keren et al 2009	nsc	**0.017**	**0.043**
-5	-37	-27	Keren et al 2009	nsc	**0.014**	**0.017**
-6	-38	-30	Keren et al 2009	nsc	**0.034**	0.053
-7	-39	-33	Keren et al 2009	nsc	**0.031**	**0.041**
4	-36	-18	Keren et al 2009	nsc	**0.003**	0.060
5	-37	-21	Keren et al 2009	nsc	**0.005**	0.065
5	-37	-24	Keren et al 2009	nsc	**0.017**	0.074
6	-37	-27	Keren et al 2009	nsc	**0.014**	**0.042**
7	-38	-30	Keren et al 2009	nsc	**0.032**	**0.032**
8	-39	-33	Keren et al 2009	nsc	**0.043**	**0.025**

Small volume correction in the locus coeruleus stereotactic coordinates reported in the *f*MRI study by Minzenberg et al (Minzenberg et al. 2008) and the *in vivo* anatomical mapping studies by Astafiev et al (Astafiev et al. 2010) and Keren et al ((Keren et al. 2009a), p.1264), applied to the statistical maps of “exploit versus explore”, “explore versus exploit” and “explorative choice in entrepreneurs”. Values shown in bold font in the p-value column survive a statistical threshold of $p < 0.05$ FWE corrected for multiple comparisons.

SVC = Small-Volume-Correction, nsc = No suprathreshold clusters.

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