DOI: 10.1002/jsc.2202 Accepted for publication in Strategic Change ©John Wiley & Sons Ltd

RESEARCH ARTICLE

Supersizing Intelligence: How the Collective Mind Builds on Dual Networks*

Matthew S. Checkley[1] | Maria Fernanda Galindo Abarca[2]

[1] Self-employed, United Kingdom
[2] University of Gloucestershire, United Kingdom

Correspondence
Matthew Checkley, 34 Great Norwood Street, Cheltenham GL502BH, UK.
Email: matthew.checkley@btinternet.com

Abstract
Strategy is collective intelligence which is optimizable via a blend of two balanced archetypes of cognitive network. Individual and collective intelligence depends on structured information flows which can be optimized for efficiency or optionality. Minds and their intelligence extend beyond the skull via interacting media such as language, technology networks, and organizations.

1 | INTRODUCTION

Strategy and organization are products of the mind. The brain, groups, organizations, or entire societies, can be understood as networks of flowing information (cf. Castells, 2000; Hutchins, 1995; Yu, Huang, Singer, & Nikolić, 2008). Human intelligence correlates with network properties of brain anatomy and its processing of information (cf. Li et al., 2009). In addition, researchers have begun to study collective intelligence (Woolley et al., 2011), and its many guises in organizational, distributed, or technology-enabled form (cf. Tollefsen, 2006). In collective intelligence, as in individual intelligence, the structure of information flows is vital to performance (cf. Woolley et al., 2011).

Given the centrality of individual and collective intelligence to so much human and organizational endeavor, a more fundamental understanding of its underlying informational structure, and future potential, is of value. But while the importance of structured networks of flowing information is widely recognized, there is no holistic theory of what, if any, network structures are most valuable to intelligence and its optimization. In addressing the challenge of structure, this paper builds a parsimonious model of both collective and individual intelligence as aggregations of two network archetypes.

To shape the argument, the article draws on research and examples from management, finance, entrepreneurship, and organizations; collective intentionality, and collective intelligence (or its absence), writ large. First, it selectively reviews literature on managerial, organizational, and collective cognition. Next, it addresses individual and collective intelligence. There is stress on scholars' attempts to cognitively link the individual and the collective, particularly in group or organizational contexts. Having identified some pivotal network- related themes, the paper then breaks new ground by considering how types of network explain and predict cognitive outcomes at different levels of analysis. Propositions are developed for researchers of collective and organizational intelligence. The paper concludes with a model of networked, multi-level cognition, and implications for theory, followed by a summary.

2 | MANAGERIAL AND ORGANIZATIONAL COGNITION

Managerial cognition is widely considered an organizational capability. Managers can re-interpret the business environment and arrange capabilities to fit emerging opportunities (Bingham, Eisenhardt, & Furr, 2007; Gavetti & Levinthal, 2000). Managerial awareness of context affects how organizations grasp opportunities and, significantly, this mediates performance outcomes. The matching of organizational capabilities to context is cognitive; a better fit causes a better out- come (Eggers & Kaplan, 2009; Taylor & Helfat, 2009). Better outcomes might also be caused by better group-working. Groups can give rise to the collective mind; it emerges wherein individuals process information with heed while cognitively contributing and subordinating their actions to collective performance (Weick & Roberts, 1993).

Both human and social capital are important to organizational performance (cf. Hitt, Bierman, Shimizu, & Kochhar, 2001). Improved organizational performance can be related to two dimensions of activity. First, there is striving for greater efficiency (broadly stated, refining established processes), which tends to mediate against, second, exploration (broadly stated, trying new processes, as concerning much entrepreneurial work). To improve performance, managers interact, discuss and share ideas. For example, the "…structure of communication networks…can affect system-level performance… when agents are dealing with a complex problem, the more efficient the network…the better the short-run but the lower the long-run performance of the system…an inefficient network maintains diversity in the system and is thus better for exploration than an efficient network…" (Lazar & Friedman, 2007, p. 667). Social structure is an established mediator of collective (and individual-level) performance (cf. Burt, 2000).

> Managerial awareness of context affects how organizations grasp opportunities and, significantly, this mediates performance outcomes. The matching of organizational capabilities to context is cognitive; a better fit causes a better outcome.

Social capital catalyzes intellectual capital. Organizations, by their very nature, tend to cultivate dense social networks and so foster intellectual capital (Nahapiet & Ghoshal, 1998). The global structure of group activity or behavior emerges from local interactions; behavioral dependencies between individuals are a substrate of distributed information processing. Organizations are, thereby, distributed information-processing systems (cf. Hutchins, 1995). They are mental entities capable of thought (Sandelands, & Stablein, 1987). An organization's processing of information exhibits complexity and bears comparison to the brain's neuroanatomy (cf. Boden, 1990).

Seen by these lights, the organization is a complex adaptive system of flowing information. It is somewhat defined by its dense social networks and their tendency to concentrate intellectual capital. Social and intellectual capital affect the organization's adaptive potential and hence its performance outcomes. Long-run performance has been tied to a blend of organizational efficiency and novelty. The next section considers the adaptive potential labelled *intelligence*.

3 | INTELLIGENCE

Intelligence involves the ability to learn from experience, adapt to new circumstances, handle abstractions, and to manipulate one's environment. (cf. Sternberg, 1999). Intelligence encompasses the individual's context, and the ability to fit to that environment. Adaption can include changing oneself and changing the environment.

Adaptation is diverse: the changes required for sports, business, science, or the arts, are all, somewhat, different. Adaptation often requires a mix of cognitive abilities. Learning, perception, memory, reasoning, and problem-solving, might all be relevant. Hence, intelligence involves a selective combination of abilities. For example, an engineer learning about a new technology might read and memorize articles and drawings, apply that learning to reason through a technical challenge and so solve engineering problems with the new technology. Until recent decades, such seemingly- obvious analysis of intelligence—incorporating its diversity, blending of abilities, and adaptive role—did not characterize much of the debate about what intelligence is and how it functions (Sternberg & Berg, 1986).

3.1 | Order in cognition and intelligence

The research reviewed so far suggests that the structure of information flows and human interactions are vital features of collective cognition. To take collective cognition—and resultant collective intelligence—seriously, is to understand how cognition flows between heads in nonindividualistic ways. In this section, the focus shifts to the causes of order in cognition. This helps jump the chasm between supposedly intracranial cognition, and extracranial, intentional phenomena, such as collective work.

There is a wealth of evidence for cognition and intelligence being structured in important ways. For example, intelligence correlates with neuroanatomical properties of the brain, such as the speed of action of neurons or the average path lengths of electrical activity across the cortex (cf. Li et al., 2009; Luders, Narr, Thompson, & Toga, 2009; Wen et al., 2011). These scholars interpret intelligence as caused by the structure of the physical systems on which it depends. Neuroanatomy is crucial to cognition and to intelligence. Order or structure in cognitive systems becomes a central theme.

Traditionally, order in cognitive systems has been conceived as the result of brain-based representation, programs, or computation. Phenomena such as development, movement, perception, or social behaviors, have been explained in terms of genetic programs, mental representations or brain-area specializations (Wagman, 2010). Yet, "the emergence of order in physical or biological systems is typically explained by means of self-organization" (Wagman, 2010, p. 46). Examples of self-organization include models of birds' flocking behavior (Reynolds, 1987), or power laws to describe animals' movement (Pennycuick, 1975). Characteristic of these examples is that patterns "emerge…from a cascade of dynamic local interaction across the various levels of a complex system…The global pattern itself is not contained within any of the local interactions but rather emerges as a lawful consequence of those interactions" (Wagman, 2010: 32). Hence, what can appear as an overall system structure is an emergent outcome of how elements of the system work, operate, or move with their neighboring elements. Theories based on dynamic self-organization lay claim to parsimonious explanatory power (Wagman, 2010), yet without being reductive (cf. Anderson, 1972, for antireductionist arguments; Campbell, 1990, for how systems theory evades reductionism).

> Seen by these lights, the organization is a complex adaptive system of flowing information. It is somewhat defined by its dense social networks and their tendency to concentrate intellectual capital. Social and intellectual capital affect the organization's adaptive potential and hence its performance outcomes.

There is, apparent in the research literature, a theoretical incommensurability between the cognitive on the one-hand, and the physical or biological on the other. Cognition and its context have been understood in different terms. But theorists point out that knowing is inseparable from doing; mind and context are entangled. Cognition is situated (Wilson, 2002). Given the context-dependence of cognition, we argue that incommensurability is a brake on advancing knowledge. A model of cognitive order would profit from terms shared with its physical and biological context, wherein common terms of analysis need not imply reduction to other sciences. Having addressed the nature of individual human intelligence, with some conceptual links to organizations, the article next considers research on collective intelligence.

3.2 | Collective intelligence

The study of human intelligence has been deep-rooted in the research literature for many decades (cf. Sternberg & Berg, 1986). Yet, organizational or collective interpretations of intelligence represent a slight stream of research in the management literature, and beyond. Moreover, if collective cognition is an accepted construct, then collective intelligence is a logical consequence.

A metric "*c*" of collective intelligence exists (Woolley, Chabris, Pentland, Hashmi, & Malone, 2010). It has predictive power for group performance in a variety of challenging tasks. Collective intelligence is caused by three factors: first, by the higher social sensitivity of group members; second, by a more even distribution of contributions from team members; third, higher intelligence is associated with more females in the group, although much of this factor is explained by females' higher social sensitivity. Neither highest-in-group nor average IQ has much explanatory power for group performance (Woolley et al., 2010).

Woolley et al. (2010), define a statistical basis for, and causes of, collective intelligence. However, their study concerns tasks taking hours (and not days or years), and the groups contain few members (less than eight in all cases). One might ask, therefore, to what extent *c* predicts outcomes for tasks of much higher complexity, specificity (e.g. technology-enabled), across tens, hundreds or thousands of workers, for months, years, or decades of effort. In short, that *c* is revealed for small groups in an experimental test-setting does not imply likewise for real-world groups or organizations.

Rather than examine group test performance and related factor analysis, Glynn (1996), grounds her definition on the adaptive potential of an organization:

> Organizational intelligence is…to process, interpret, encode, manipulate, and access information in a purposeful, goal-directed manner, so it can increase its adaptive potential… [and] is related to solving problems, meeting objectives, and making effective responses to environmental challenges… (Glynn, 1996, p. 1088)

Organizational intelligence is positively correlated with performance outcomes. It can be inextricable from organizational routines, from social process, and from organizational culture (Glynn, 1996).

3.3 | Summarizing the literature on collective intelligence

Managers mindfully subordinate their individual interests to shared concerns to form a collective mind. Such a mind in adaptive pursuit of goals shows collective intelligence. On this view, managerial cognition springs from striving for higher collective intelligence. It is inextricably tied to action. Furthermore, statistical research shows the potency of the collective mind is little-dependent on individuals' cognitive powers, and much-dependent on their ways and patterns of interrelating. In organizations, those patterns liken to the complex structure of neuroanatomy in the human brain. The structure of flowing information is material to collective intelligence.

4 | EXTENDING THE MIND

In attempting to understand how individual and collective cognition combine, prior sections discuss networks of information. Because cognition—collective or otherwise—is inextricably embedded in con- text (cf. Hutchins, 1995), the terms in which one analyzes mind and context should be shared. Complex systems offer such promise; they non-reductively account for both the structure of cognition and its embedding-in-context (Wagman, 2010).

This section introduces the Extended Mind (Clarke & Chalmers, 1998). This proffers an understanding of how the mind interacts with its context, and it links individual to collective cognition.

> Furthermore, statistical research shows the potency of the collective mind is little-dependent on individuals' cognitive powers, and much-dependent on their ways and patterns of interrelating. In organizations, those patterns liken to the complex structure of neuroanatomy in the human brain.

The Extended Mind relates to external artifacts being used in ways equivalent to internal cognition (Clark & Chalmers, 1998). On this view, extracranial objects or information—for example, the note to buy milk on the way home—act with functional equivalence to internally-memorizing the need to buy milk. The intracranial mind and its context are now coupled via the note. Thereby, the mind, as usually understood, is extended. The criterion for mind extension is that, with coupling, the artifacts or processes in question have equivalence to the coupled internal processes.

Language is a foremost means by which cognition is extended (Clark & Chalmers, 1998). The Extended Mind can include social ties and culture (cf. Hutchins, 1995; Logan, 2007). With the mind being so embedded in its biological, physical, and conceptual environs, an understanding of cognitive structure should take account of both intracranial processes and their extracranial, functional linkages. In this way, boundaries between individual and, for example, organizational intelligence, are pervious; both extend beyond the skull of any individual and both interact with context. Cognition is externalized and de-individualized. There is now no solid divide between the cognition of the manager and the organization (cf. Tollefsen, 2006, for a parallel argument). They can co-depend via such means as routines or databases.

The next section breaks new ground by developing the novel idea of invariant patterning mechanisms in Extended Mind cognition. Patterns come from specific principles of self-organization (Wagman, 2010). Understanding such structures bids new ways to cultivate collective intelligence. Later, research propositions are derived from the observation of common, intelligence-causing patterns of information flow.

4.1 | The (extended) mind as network archetypes

This section addresses the structure of optimal networks. The argument so far—entirely built on well-established research findings, albeit from diverse fields of study—has established that structured information flows are functional to intelligence at both individual and collective levels of analysis. Moreover, different levels of network interact—via the Extended Mind—in important ways. Specific network archetypes are now hypothesized as underlying cognition at both intra- and extracranial levels of analysis. Constructal law (Bejan, 1997) is discussed first. Subsequently, Small World networks (cf. & Buchanan, 2003) are addressed.

4.1.1 | The first principle of optimal flow: Efficiency

Constructal law proposes self-organization within flowing physical systems (Bejan, 1997; Bejan & Lorente, 2010). Its disciplinary origin is thermal dynamics. Constructal law notes that if a flowing system— such as lightning or animals' migratory paths—has freedom to adapt its configuration, then the flow is eased over time. Moreover, that flow tends to a tree-like, or dendritic, pattern.

Constructal law asserts, "for a finite-size flow system to persist… it must evolve…such that it provides easier access to the currents that flow" (Bejan & Merkx, 2007, p. 2). The law identifies a general pattern—not an exact structure—that freely-adapting flowing systems display. Constructal systems are often considered in terms of flow- maximization, or, similarly, flow-time minimization. The flow can be (bidirectionally) from a volume, area or line, to a point.

Examples of biological Constructal flow include the lungs, blood flow, neurons, and much from the botanical world. These all describe tree-like, or dendritic, patterns. Constructal informational flow is noted in language use, database searches, the movement of information between universities (Bejan, 2009), information within financial markets (Sweo & Pate, 2010), or the structure of Guanxi networks (Chester, 2016). Constructal physical designs include street layouts, the spatial distribution of settlement sizes, river deltas, and thermal flow across metals (Bejan & Merkx, 2007). Hence, Constructal law applies to biological, conceptual, and physical—either natural or man-made—systems. It specifies in measurable terms how flowing shapes are created, change, and optimized. Given the importance of efficiency and optimization to organizations, Constructal law offers insight (**Figure 1**).

> Constructal law notes that if a flowing system—such as lightning or animals' migratory paths—has freedom to adapt its configuration, then the flow is eased over time. Moreover, that flow tends to a tree-like, or dendritic, pattern.

A few conditions are necessary for Constructal law to manifest: freedom for the flow to adapt; a material flow volume (e.g. one can view, in Constructal terms, the migratory paths of 1,000 of buffalo, but not 10); there must be memory in the system (e.g. paths smoothed through the brush and made easier to walk); and there must be places of easier and harder flow, that is, the region hosting the flow system cannot be eternally uniform in resisting the flow.

Constructal properties of the brain, and the environment in which it is situated, have implications for our understanding of *intelligence*. Li et al. (2009) hypothesize that higher intelligence derives from higher global efficiency of the brain's anatomical network. They find that general intelligence scores are significantly correlated with net- work properties; shorter path lengths; and higher overall efficiency. Efficiency in neural architecture is a foundation of intelligence. In addition, reaction speed is positively correlated with intelligence for complex tasks (Schweizer, 2001), while withered (thinner, slower acting) neurons are associated with lower intelligence (cf. Comery et al., 1997).

In summary, Constructal law—essentially a Principle of Least Effort (Zipf, 1949)—describes order in flowing systems. The research literature shows that efficient cognition correlates with intelligence. But if efficient cognition is comprised of a salient flowing system, then its optimization is Constructal. Intelligence is efficient, and efficiency is Constructal. Moreover, the idea of the Extended Mind suggests that cognition can be both externalized and de-individualized. If cognition is extended, then, by implication, so is intelligence. This suggests that more intelligent

FIGURE 1 Constructal design: A brain cell and lorry tracks from clearing Woodland. Photograph by kind permission: airpictures.se. [Color figure can be viewed at wileyonlinelibrary.com]

individuals create more efficient Constructal flows in service of the Extended Mind. Put another way, a group or individual can operate within salient Constructal flows to become more intelligent. Constructal law supports common terms of analysis of both intracranial cognition, and the Extended (or organizational) Mind.

To distil: given that comparable organizations, with similar goals, vary in terms of their efficiency in pursuing those goals, it is argued that the greater efficiency of an organization can be explained in terms of its embedding in Constructal networks, for example, for gaining or sharing rapid-fire information, or crafting lean logistical networks. So, when comparing the same complex information flows demanding efficiency across peer organizations:

Proposition 1 *More efficient organizations employ more Constructal-like informational flows than peers.*

4.1.2 | The second principle of optimal flow: Optionality

While Constructal law describes optimally energy-efficient directed flow systems, the more widely known Small World networks appear in cases of agency. Small Worlds are optimal in terms of offering the shortest average path length between randomly-selected nodes, and hence the optionality of time- or energy-constrained agents travelling that network. They optimize economical optionality but, unlike Constructal networks, not energy efficiency in the case of impassively directed flow.

A Small World network is a mathematical graph in which most nodes are not directly connected, but, in most cases, any two randomly selected nodes are connected indirectly via a small number of other nodes. More formally, a Small World is a network in which the distance between two randomly chosen nodes (i.e., the number of node-jumps required to travel between the two chosen nodes) grows proportionally to the logarithm of the number of nodes in the network (**Figure 2**).

Small Worlds are observable in human and animal social networks, the physical structure of the internet, and in transport networks, such as national and international flight paths via various hub airports at major cities (Buchanan, 2003). Anatomical connections in the brain show small world topology (Sporns, Chialvo, Kaiser, & Hilgetag, 2004), as does the pattern of synchronized electrical activity between cortical regions (Yu et al., 2008). Creative processes within the brain exhibit Small Worlds (cf. Schilling, 2005). Similarly, Small Worlds of interfirm alliances, or interpatent-holder cooperation, increase innovation productivity (cf. Fleming, King, & Juda, 2007).

Small Worlds show dense, local clusters (also known as cliques), and a short path between any randomly chosen pair of nodes through- out the network. This structure is economical in the brain, in the sense of minimizing wiring costs to carry highly dynamic, complex information flow (cf. Langera, von Bastian, Wirza, Oberauerb, & Janckea, 2013). Consistently, Small World brain anatomy shows specialized and partially segregated functional regions, alongside distributed-yet-integrated processing throughout the entire brain.

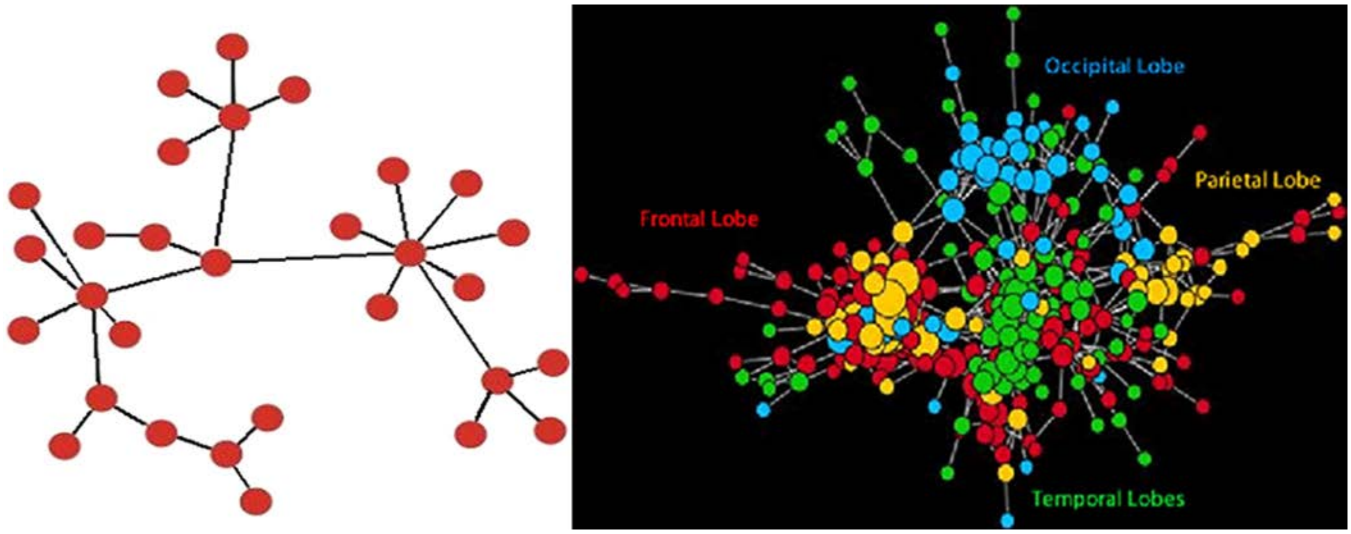

FIGURE 2 Small world networks: In abstract and in cortical activity. [Color figure can be viewed at wileyonlinelibrary.com]

In parallel with Constructal law, Small Worlds appear both within the brain and within its shared, collective and Extended cognitive expressions. The mind is externalizing Small World networks—with its uses of social networks, IT networks, or linking of ideas, for example— just as it is externalizing Constructal forms. We would expect, there- fore, that more innovative organizations (than peers) are embedded in larger and faster-flowing Small Worlds of innovation-relevant information. If, for example, pursuing novel solutions to recognized problems, the greater innovative productivity of an organization can be explained by its position in Small Worlds of salient information flow:

Proposition 2 *More innovative organizations employ Small World networks of greater size and diversity than peers.*

In summary, the mind is embedded in (at least) two archetypes of externalized, nonindividualistic informational network. Both Constructal and Small World networks tie individual and collective cognition. Such optimizations mediate organizations' performance outcomes.

4.2 | The Optimized Extended Mind

The prior sections imply that minds co-depend both on context (e.g., technologies within and beyond the group), and on other minds, to collectivize. Individual and organizational mind can be analyzed commensurately.

The cognitive-network perspective means that the structure of flowing information is the vital feature. Structure mediates both individual and collective intelligence. Specific network archetypes are identified. Significantly, these archetypes are common to both intra- and extracranial phenomena. But how might intra- and extracranial networks interact? The article now considers how archetypes conjoin across levels of analysis.

An example illustrates multilevel analysis. The brains of innovators manifest Small World networks of cortical activity as they strive for novel insights (Schilling, 2005). Moreover, innovators form Small World social networks as they share and develop ideas (Fleming et al., 2007). The combination of the same network archetype at different levels of analysis—in this example, cranial, interpersonal, and interfirm—suggests that option-richness at one level of salient information flow supports another. System-level innovation-potential is optimized. A parallel argument is made for multilevel Constructal networks and the drive for efficiency. For example, highly efficient flows of financial information manifest Constructal networks (Sweo & Pate, 2010), while the super-nor- mal reaction speed of traders responding to information (Coates, Gurnell, & Ruchini, 2009) suggests highly efficient (human) neural networks in action. One expects, therefore, that organizations most attuned to either efficiency or innovation, to have, compared with peers, more extensive networks of information of self-similar archetype:

Proposition 3a *Organizational efficiency increases with more Constructal information flows across levels of analysis; intra- to extracranial.*

Proposition 3b *Organizational innovation increases with more Small World information flows across levels of analy- sis; intra- to extracranial.*

In this way, complex and far-reaching Extended Mind cognition (as one might associate with an organization) is structured in hierarchical, self-similar networks of flowing information. Both Constructal and Small World networks have the property of being self-similar and hierarchical, or scale-free. Such forms are fractal (cf. Briggs, 1992).

4.3 | Balancing efficiency and optionality

The prior sections, on Constructal and Small World networks, raise the issue of how and why efficient and option-rich systems optimally blend. The blending challenge is widespread. For example: organizational Exploitation versus Exploration (March, 1991); Lean versus Agile distribution networks (Christopher, 2000); Weberian bureaucracy versus organic organizational structure (cf. Child, 1972); or the computational challenge of seeking more-refined versus novel algorithms (cf. Gittins, 1979). As March notes, "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 the 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" (1991, p. 71).

> The combination of the same network archetype at different levels of analysis—in this example, cranial, interpersonal, and interfirm—suggests that option-richness at one level of salient information flow supports another.

Yet, with some notably constrained and mathematical exceptions—cf. the many papers building on Gittins (1979)—the challenge of optimal blending is unmet. March laments, "Specifying the optimal mix of exploitation and exploration is difficult or impossible." (2006, p. 205). Nevertheless, beneficial emphasizes in the blend have been identified. For example, at the individual level, Mom et al. (2007) found that the more a manager acquires top-down and bottom-up knowledge flows, or top-down and horizontal knowledge flows, the higher the levels of exploration and exploitation activities…managers have both a short-term and a long-term orientation (cf. O'Reilly & Tushman, 2004; Probst & Raisch, 2005; Raisch, Birkinshaw, Probst, & Tushman, 2009, p. 687).

Exploitation is favored in conditions of high predictability, fewer potentially-rich choices, and less time-to-see-pay-offs. Exploration is preferred contrariwise; with less predictability, more tempting choices, and more time-to-explore (cf. March, 2006). That the human brain is the most-evolved known solution to the blending problem suggests a model of optimization. In this vein, researchers have begun to tackle how human brains combine the two modes of cognition (Berger-Tal, Nathan, Meron, & Saltz, 2014; Cohen, McClure, & Yu, 2007; Laureiro-Martínez, Brusoni, Canessa, & Zollo, 2015). One expects, therefore, that the exploitation versus exploitation dilemma manifests as efficient versus option-rich informational networks. This, in turn, implies a blend of Constructal and Small World networks attuned to the organization's needs:

> **Proposition 4a** *For organizations, less time, choice, or uncertainty, correlates with proportionally more use of efficient Constructal networks, and less use of option-richSmall World informational networks.*

> **Proposition 4b** *For organizations, more time, choice, or uncertainty, correlates with proportionally less use of efficient Constructal networks, and more use of option-richSmall World informational networks.*

5 | DEVELOPING A NEW MODEL

To review the argument: innovations, financial transactions, organizations, strategies, language, or research itself, are all products of the mind. Moreover, these phenomena manifest common structures; Constructal and Small World networks of flowing information. Such structures are observable in the human brain and its neuroanatomy, in technological or social networks, and beyond. Moreover, these different levels of network (e.g., neuroanatomical, linguistic, and interorganizational) are interactive and co-dependent. The existence of both network archetypes, and their commonality, both intra- and extracranially, is well-established. In both organizational and neuroanatomical cases, links between structure and performance outcomes are also well-established.

Given that both Constructal and Small World networks are optimizations—of, respectively, efficiency and economic optionality, which can be linked to both evolutionary and market-competitive survival—it is argued that common forces in nature created common structures in brains and their (historically expanding) cognitive niche. It is further presumed that change is directed by minds to achieve goals. The Extended Mind gives theoretical support to the associations between individual cognition and tool-use, language, organizational routines, collective thinking, etc. It is upon this chain of evidence and reasoning that this paper rests.

Densely-shared informational structures—at combined levels of analysis—are what matter to collective intelligence and hence to collective action. The argument reduces to the idea that dual archetypes of fractal (i.e., hierarchical, self-similar, and scale-free) cognitive network are the essence of strategy. The model predicts cognitive advantages for the organization or individual with bigger and better- structured flows of information.

This article attempts to understand the structures on which cognition optimally depends. Table 1 below summarizes the model; its assumptions, the consequent propositions, and implications. Later, the article addresses further implications for research.

TABLE 1 A network model of collective intelligence

A. Assumptions
Intelligent collective action depends on extensive and complex, bidirectional, co-dependent, evolving networks of information; of neurons, language usage, IT networks, logistics, of interfirm alliances, etc.
Organizations exist, through distilled social and intellectual capital, to direct collective intelligence towards shared goals.
Organizations blend processes of exploration and exploitation to increase their adaptive potential.
B. Propositions
More efficient organizations employ more Constructal-like flows than peer organizations.
More innovative organizations employ Small World networks of greater diversity than peer organizations.
More efficient / innovative networks tie proportionally more to self-similar archetypes across levels of analysis.
The blend of the dual network archetypes conforms to patterns associated with the explore versus exploit dilemma.
C. Implications
Collective work concerns the cultivation of collective intelligence. Managers should foster a balance of the two archetypes of optimal goal-directed informational networks. Information flows—and hence intelligence—are optimizable at diverse and combined levels of analysis.

5.1 | Implications for research

Prior research says a lot about managerial cognition, a little about collective cognition, and very little about collective intelligence. Given the near-equivalence of high collective intelligence and successful collective action or strategizing, a vital question is how to increase the potency of organizational cognition.

This article supports a view of organizational work and strategy as cognitive, situated (cf. Hodgkinson & Healey, 2011), complex and adaptive (cf. Wagman, 2010), and thus avoiding the pitfalls of reductionism (cf. Lindebaum & Zundel, 2013). Cognitive research in organizations, it is argued, should incorporate multiple levels of analysis (cf. Huff, 1997). This article offers a novel analysis of neuroanatomy blended with organizational processes.

Extant research discusses how cognition—collectively or other- wise—is important to collective effort (cf. Gavetti & Rivkin, 2007). A performant feature of cognition is informational network structure (cf. Li et al., 2009). This article attempts to pin-down what structures of complex interaction are optimal with respect to time pressures, task- complexity or uncertainty (building on, for example, Lazar & Friedman, 2007). But, in contrast with nearly all prior work on managerial cognition (cf. Nahapiet & Ghoshal, 1998, for an engaging exception that focuses on social networks) this article takes the emphasis off individuals' cognitive endowments and, rather, places it firmly onto informational networks. These are, in terms of size, speed, or optionality, measurable and comparable between brains, groups or organizations. Moreover, the article proposes that all salient complex processes are optimizable in terms of just two network archetypes and their blending. Such networks have fractal properties. This forms a parsimonious model of collective intelligence. This, in turn, offers a way to explain, predict or improve cognition, and its related performance outcomes, at individual or collective levels of analysis.

This article contributes to knowledge by focusing on the structure of Extended Mind cognition. It specifies the pattern of information flow across diverse and complex phenomena in which minds conjoin with organizations to tackle—as befits their purpose—large, dynamic, and sophisticated challenges. That such patterns are optimal aids normative theorizing.

In sum, this article is a call for more efforts to see collective action in terms of structured, multilevel information flow. Such flows can be optimized. Improvement can be linked to increased collective intelligence, and hence to better strategy and organizational outcomes.

5.2 | Implications for practice

Cognitive efficiency and optionality should be trained and cultivated. Because organizational outcomes depend on collective intelligence (applied to shared goals) at multiple, co-dependent levels of analysis, development also should be considered at all levels; the individual brain, the group, the organization, and the supra-organization (by building intra-and interorganizational networks of appropriate form and blend).

The model predicts that artificially intelligent agents will similarly benefit from network structures of flowing information. In addition, the framework can help explain the dire performance outcomes of organizations endowed with luminous individual brilliance, coupled with disjointed flows of task-relevant information (the crushing fate of talent-rich Long Term Capital Management offers a trenchant case, cf. Lowenstein, 2000).

Organizations can be guided by the Propositions within. For example, managers seeking more innovation should foster diverse and interactive Small World networks. Effort could emphasize improved neuroplasticity, new narratives, and language in which to couch challenges, diverse group or intraorganizational working, and embedding the organization in information-rich and diverse interorganizational networks. These are all (interacting) measures likely to increase the innovative potential of the firm.

The future is one of both individuals and collectives embedding within bigger, information-richer, and faster networks (cf. Castells, 2000). Attention to network structures, their extensiveness, and the balance of dual archetypes, will be rewarded with cognitive advantages for the agencies in question.

5 | Limitations of the Model

This section addresses the limitations of the model. The article engages with the idea of optimal networks. But some organizational networks are either irrelevant or damaging (cf. Alvesson & Spicer, 2012). The pursuit of optimality aids normativity and parsimony, but lacks descriptive adequacy.

Networks are described as self-organizing while referring to managerial agency in their development. Yet, by definition, self-organizing networks are susceptible to little managerial agency. Hence, the article serves, indirectly, as an argument for the narrow limits of free-will and, likewise, the vast extent of partly-determined human action. On this view, thoughts, capabilities, and actions are both trammeled by, and catalyzed by, habitual networks. That such networks are a product of the mind does not wholly liberate the Extended Mind from its self-generated tracks. More broadly, to what extent are (undiscussed) variables intervening between, say, intracranial intentionality and organizational action?

6 | SUMMARY

Cognitive advantages (i.e., wherein choices matter) are invariant within the indeterminacies of evolutionary systems. The question of how to enhance managerial cognition is fundamental within strategy.

> Effort could emphasize improved neuroplasticity, new narratives, and language in which to couch challenges, diverse group or intraorganizational working, and embedding the organization in information-rich and diverse interorganizational networks

Strategy and organizational work is likened to collective (Extended Mind) intelligence. Evolutionary and competitive forces for greater efficiency and optionality are formative of common, complex network archetypes within the biological brain and its context. The mind reorders the world, and the world reorders the mind. Higher intelligences have, in both cases, the capacity for more reordering.

In sum, organizations are a form of extensible, ameliorable, and specialized intelligence. They are, optimally, an outcome of two balanced archetypes of fractal cognitive network. Such an understanding, if proven valid, solves some obdurate challenges of improving organizational outcomes.

ACKNOWLEDGMENTS

This article benefited from suggestions and critiques offered by Henk Alles, David Dawson, Jim Keane, Clive Kerridge, Mark Ashton Smith, Andre Spicer, Neil Towers, and Jeffrey Wagman. The authors are indebted to Editor in Chief, Carlo Milana, and the reviewers at *Strategic Change*.

REFERENCES

Alvesson, M., & Spicer, A. (2012). A stupidity-based theory of organizations. *Journal of Management Studies*, *49*, 7.

Anderson, P. W. (1972). More is different: Broken symmetry and the nature of the hierarchical structure of science. *Science*, *177* (4047), 393–396.

Bejan, A. (1997). Constructal tree network for fluid flow between a finite- size volume and one source or sink. *Revue General de Thermique*, *36*, 592–604.

Bejan, A. (2009). Two hierarchies in science: The free flow of ideas and the academy. *International Journal of Design and Nature and Ecodynamics*, *4*(4), 1–9.

Bejan, A., & Lorente, S. (2010). The constructal law of design and evolution in nature. *Philosophical Transactions of the Royal Society B*, *12*(365), 1335–1347.

Bejan, A., & Merkx, G.W. (Eds.). (2007). *Constructal theory of social dynamics*. New York, NY: Springer.

Berger-Tal, O., Nathan, J., Meron, E., & Saltz, D. (2014). The exploration- exploitation dilemma: A multidisciplinary framework. *PLoS One*, *9*(4), e95693.

Bingham, C. B., Eisenhardt, K. M., & Furr, N. R. (2007). What makes a process a capability? Heuristics, strategy, and effective capture of opportunities. *Strategic Entrepreneurship Journal*, *1*(1–2), 27–47.

Blackburn, S. (1993). *Essays in quasi-realism*. Oxford, UK: Oxford University Press.

Boden, M. (1990). *The creative mind: Myths and mechanisms*. London, UK: Weidenfield and Nicholson.

Briggs, J. (1992). *Fractals: The patterns of chaos*. London, UK: Thames and Hudson.

Buchanan, M. (2003). *Nexus: Small worlds and the groundbreaking theory of networks*. ISBN 0–393-32442-7. New York, NY: W. W. Norton and Company, Inc.

Burt, R. S. (2000). The network structure of social capital. *Research in Organizational Behavior. 22*, 345–423.

Campbell, D. T. (1990). Levels of organization, downward causation, and the selection-theory approach to evolutionary epistemology. In E. Tobach, & G. Greenberg (Eds.), *Scientific methodology in the study of mind: Evolutionary epistemology* (pp. 1–17). Hillsdale, NJ: Erlbaum.

Castells, M. (2000) The contours of the network society, *Foresight*, *2(*2), 151–157.

Chester, H. (2016). Global channels of successful immigrant entrepreneurs illustrate the constructal law. *International Journal of Heat and Technology*, *34*(Special Issue 1), S29–S36.

Child, J. (1972). Organization structure and strategies of control: A replication of the Aston study. *Administrative Science Quarterly*, *17(*2), 163–177.

Clark, A., & Chalmers, D. J. (1998). The extended mind. *Analysis*, *58*, 10–23.

Coates, J. M., Gurnell, M., & Ruchini, A. (2009). Second-to-fourth digit ratio predicts success among high-frequency financial traders. *Proceedings of the National Academy of Sciences United States of America*, *106*, 623–628.

Cohen, J. D., McClure, S. M., & Yu, A. J. (2007). Should I stay or should I go? How the human brain manages the trade-off between exploitation and exploration. *Philosophical Transactions of the Royal Society B*, *362*, 933–942.

Comery, T. A., Harris, J. B., Willems, P. J., Oostra, B. A., Irwin, S. A., Weiler, I. J., & Greenough, W. T. (1997). Abnormal dendritic spines in fragile- X knockout mice: Maturation and pruning deficits. *Proceedings of the National Academy of Sciences United States of America*, *94*, 5401–5404.

Christopher, M. (2000). The Agile supply chain: Competing in volatile markets. *Industrial Marketing Management*, *29*(1), 37–44.

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., & May, A. (2004). Neuroplasticity: Changes in grey matter induced by training. *Nature*, *427*, 311–312.

Eggers, J. P., & Kaplan, S. (2009). Cognition and renewal: Comparing CEO and organizational effects on incumbent adaptation to technical change. *Organization Science*, *20*(2), 461–477.

Engel, A. K., & Singer, W. (2001). Temporal binding and the neural correlates of sensory awareness. *Trends in Cognitive Science*, *5*(1), 16–25.

Fleming, L., King, C., & Juda, A. (2007). Small worlds and regional innovation. *Organization Science*, *18*, 938–954.

Fodor, J. (1975). *The language of thought*. New York, NY: Crowell.

Gavetti, G., & Levinthal, D. (2000). Looking forward and looking backward: Cognitive and experiential search. *Administrative Science Quarterly*, *45*(1), 113–137.

Gavetti, G., & Rivkin, J. W. (2007). On the origin of strategy: Action and cognition over time. *Organization Science*, *18*(3), 420–439.

Gittins, J. C. (1979). Bandit processes and dynamic allocation indices. *Journal of the Royal Statistical Society Series B*, *41*(2), 148–177.

Glynn, M. A. (1996). Innovative genius: A framework for relating individual and organizational intelligences to innovation. *The Academy of Management Review*, *21*(4), 1081–1111.

Hitt, M.A., Bierman, L., Shimizu, K., & Kochhar, R. (2001). Direct and moderating effects of human capital on the strategy and performance in professional service firms: A resource-based perspective. *Academy of Management Journal*, *44*, 13–28.

Hodgkinson, G. P., & Healey, M. P. (2011). Psychological foundations of dynamic capabilities: Reflexion and reflection in strategic management. *Strategic Management Journal*, *32*, 1500–1516.

Huff, A. S. (1997). A current and future agenda for cognitive research in organizations. *Journal of Management Studies*, *34*(6), 947–952.

Hutchins, E. (1995). *Cognition in the wild*. Cambridge, MA: MIT Press.

Langera, N., von Bastian, C. C., Wirza, H., Oberauerb, K., & Jänckea, L. (2013). The effects of working memory training on functional brain network efficiency. *Cortex*, *49*(9), 2424–2438.

Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies*. Cambridge, MA: Harvard University Press.

Laureiro-Martínez, D., Brusoni, S., Canessa, N., & Zollo, M. (2015). Understanding the exploration–exploitation dilemma: An fMRI study of attention control and decision-making performance. *Strategic Management Journal*, *36*, 319–338.

Lazer, D., & Friedman, A. (2007). The network structure of exploration and exploitation. *Administrative Science Quarterly*, *52*, 667–694.

Li, Y., Liu, Y., Li, J., Qin, W., Li, K., Yu, C., &Jiang, T. (2009). Brain Anatomical Network and Intelligence. *PLoS Computational Biology*, *5*(5).

Lindebaum, D., & Zundel, M. (2013). Not quite a revolution: Scrutinizing organizational neuroscience in leadership studies. *Human Relations*, *66*(6), 857–877

Logan, R. K. (2007). *The extended mind: The emergence of language, the human mind and culture*. Toronto, Canada: University of Toronto Press.

Lowenstein, R. (2000). *When genius failed: The rise and fall of long-term capital management*. Manhattan, NY: Random House Trade Paperbacks.

Luders, E., Narr, K. L., Thompson, P. M., & Toga, A. W. (2009). Neuroanatomical correlates of intelligence. *Intelligence*, *37*(2), 156–163.

Mann, E. O., Radcliffe, C. A., & Paulsen, O. (2005). Hippocampal gamma- frequency oscillations: From interneurones to pyramidal cells, and back. *The Journal of Physiology*, *562*(1), 55–63.

March, J. G. (1991). Exploration and exploitation in organized learning. *Organizational Science*, *2*(1).

March, J. G. (2006). Rationality, foolishness, and adaptive intelligence. *Strategic Management Journal*, *27*, 201–214.

Mom, T. J. M., van den Bosch, F. A. J., & Volberda, H. W. (2007). Investigating managers' exploration and exploitation activities: The influence of top-down, bottom-up, and horizontal knowledge inflows. *Journal of Management Studies*, *44*(6), 910–931.

Nahapiet, J., & Ghoshal, S. (1998). Social capital, intellectual capital, and the organizational advantage. *The Academy of Management Review*, *23*(2), 242–266.

O'Reilly, C. A., & Tushman, M.L. (2004). The ambidextrous organization. *Harvard Business Review*, *82*, 74–81.

Pennycuick, C. J. (1975). Mechanics of flight. In D.S. Farner, J.R. King, & K. C. Parkes (Eds.), *Avian biology* (Vol. *5*, pp. 1–75). New York, NY: Academic Press.

Probst, G., & Raisch, S. (2005). Organizational crisis: The logic of failure. *Academy of Management Executive*, *19*(1), 90–105.

Raisch, S., & Birkinshaw, J. (2008). Organizational ambidexterity: Antecedents, outcomes, and moderators. *Journal of Management*, *34*, 375–409.

Raisch, S., Birkinshaw, J., Probst, G., & Tushman, M.L. (2009). Organizational ambidexterity: Balancing exploitation and exploration for sustained performance *Organization Science*, *20*(4), 685–695.

Reynolds, C. (1987). Flocks, herds, and schools: A distributed behavioral model. *Computer Graphics*, *21*, 25–34.

Sandelands, L. E., & Stablein, R. E. (1987). The concept of organization mind. In N. DiTomaso, & S. Bachrach (Eds.). *Research in the sociology of organizations* (Vol. *6*, pp. 135–161). Greenwich, CT: JAI Press.

Schilling, M. A. (2005). A small-world network model of cognitive insight. *Creativity Research Journal*, *17*(2 and 3), 131–154.

Schweizer, K. (2001). Preattentive processing and cognitive ability. *Intelligence*, *29*(2), 169–186.

Simon, H. (1947). *Administrative behavior*. New York, NY: Macmillan.

Smith, W. K., & Tushman, M. L. (2005). Managing strategic contradictions: A top management model for managing innovation streams. *Organization Science*, *16*(5), 522–536.

Sporns, O., Chialvo, D.R., Kaiser M., & Hilgetag, C.C. (2004). Organization, development and function of complex brain networks. *Trends in Cognitive Sciences. 8*(9), 418–425.

Spruston, N. (2008). Pyramidal neurons: Dendritic structure and synaptic integration. *Nature Reviews Neuroscience*, *9*(3), 206–221.

Sternberg, R. J. (1999). The theory of successful intelligence. *Review of General Psychology*, *3*, 292–316.

Sternberg, R. J., & Berg, C. A. (1986). Quantitative integration: Definitions of intelligence: A comparison of the 1921 and 1986 symposia. In R. J. Sternberg, & D. K. Detterman (Eds.), *What is intelligence? Contemporary viewpoints on its nature and definition* (pp. 155–162). Norwood, NJ: Ablex.

Sweo, R., & Pate, S. (2010). Understanding currency market dynamics through constructal theory: A managerial perspective. *Journal of Inter- national Management Studies*, *5*(1), 75–81.

Taylor, A., & Helfat, C. E. (2009). Organizational linkages for surviving tech- nological change: Complementary assets, middle management, and ambidexterity. *Organization Science*, *20*(4), 718–739.

Tollefsen, D. (2006). From extended mind to collective mind. *Cognitive Systems Research*, *7*, 140–150.

Wagman, J. B. (2010). What is responsible for the emergence of order and pattern in psychological systems? *Journal of Theoretical and Philosophical Psychology*, *30*(1), 32–50.

Weick, K. E., & Roberts, K. H. (1993). Collective mind in organizations: Heedful interrelating on flight decks. *Administrative Science Quarterly*, *38*(3), 357381.

Wen, W., Zhu, W., He, Y., Kochan, N., Reppermund, S., Slavin, M.J., Sachdev, P. (2011). Discrete neuroanatomical networks are associated with specific cognitive abilities in old age. *Journal of Neuroscience*, *31*, 1204–1212.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin and Review*, *9*(4), 625–636.

Woolley A. W., Chabris, C. F., Pentland, A., Hashmi, N., & Malone, T.W. (2010). Evidence for a collective intelligence factor in the performance of human groups. *Science*, *330*, 686–688.

Yu, S., Huang, D., Singer, W., & Nikolić, D. (2008). A small world of neuronal synchrony. *Cerebral Cortex*, *18*(12), 2891–2901.

Zipf, G. K. (1949). *Human behavior and the principle of least effort*. Boston, MA: Addison-Wesley.

AUTHOR BIOGRAPHY

Matthew Checkley is self-employed. He has a commercial background in industry analysis and entrepreneurship. His research blends net- work science and strategy.

Maria Fernanda Galindo Abarca is a specialist in neo-institutional theory and NGO Management. She has run charitable organizations and worked in academia. She teaches ethics and leadership at the University of Gloucestershire.