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Using functional neuroimaging to advance entrepreneurial cognition research

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ABSTRACT

This article advances current understandings of why and how functional neuroimaging can enrich the study of entrepreneurship. We discuss the foundations of this cross-disciplinary research area and its evolving boundaries, focusing on explaining and providing actionable insights on how two of the most widely used brain-imaging methods can be leveraged for use in entrepreneurship research. We provide guidelines aimed to equip entrepreneurship scholars with the fundamentals needed to design and evaluate research involving these neuroscience methods. In so doing, we delineate examples related to entrepreneurial cognition and propose several ways in which this domain of research can be enhanced with neuroimaging.

KEYWORDS
Entrepreneurship; organizational neuroscience; cognition; methods; EEG; fMRI

Introduction

Recently, advancements in both neuroscience scholarship and technology (e.g., wireless electroencephalography [EEG]) have gained traction among management and entrepreneurship researchers (Becker et al., 2011; Nicolaou & Shane, 2014).[1] While neuroscience, and functional neuroimaging in particular, are opening novel opportunities to explore the neurophysiological substrates of mental processes and corresponding behaviors (see for review, e.g., Yarkoni et al., 2010)—with a few exceptions (e.g., Lahti et al., 2019; Shane et al., 2020)—they have made little empirical inroads into the entrepreneurship literature thus far.[2]

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[1]Scholars have debated on whether the use of neuroscience in entrepreneurship research shall be considered a field in its own right (e.g., Krueger & Welpe, 2014), within the biology of the entrepreneurship framework (e.g., Nofal et al., 2018), or be incorporated into organizational neuroscience (e.g., Ward et al., 2017). To ensure the applicability of the insights presented in this work to ampler context and given the recent establishment of the Interest Group in Organizational Neuroscience (NEU) at the Academy of Management (see neu.aom.org), here, we will largely refer to the latter perspective.

[2]We use the adjective "mental" to refer to processes and functions that individuals evoke with their minds (Healey et al., 2018). In line with the neuroscience literature, this term is similar to cognitive functioning, yet it offers coverage of a broader range of activities including thinking (Cerf et al., 2010), volition (Cerf & Mackay, 2011), and emotions (Massaro, 2020), all of which are relevant to entrepreneurial cognition. Likewise, we use the term "neuroimaging" to highlight the functional aspects of brain imaging techniques, and the word "neuroscience" to refer to "cognitive neuroscience" and its broadest meaning, thereby including the declinations and fields of decision, social, and affective neuroscience.

This fact is surprising given that Nicolaou and Shane (2014, p. 99), among other authors, have previously recognized that neuroscience in entrepreneurship "holds the potential to address important unanswered questions in the field." Knowledge and methods from neuroscience have the potential to be used in entrepreneurship research to both advance and integrate traditional participant assessments, such as those using subjective recall, self-reported responses, and surveys to infer subjects' views, states, or traits. By using such approaches, entrepreneurs' cognition and mental processes, in essence, are studied as either "unobservable" phenomena or only observed indirectly. Moreover, research participants may face difficulties in articulating their internal mental ruminations (Trapnell & Campbell, 1999) and at times be biased by peer-group answers or social desirability (Holbrook et al., 2003), thus not always ensuring the provision of "objective" information. Fortunately, neuroimaging can help to partly address such concerns by providing a complementary means to further probe entrepreneurial cognitive processes via analyses of "observable" physiological data and signals that are beyond the participants' direct awareness (Waldman et al., 2019). Thus, undertaking a neuroscience approach in entrepreneurship research can assist scholars in supplementing existing methods of inquiry, while offering an innovative lens to access relevant mental processes.

At the same time, some caveats apply. First, neuroscience is not and cannot be seen as a "panacea" able to offer absolute or perfect insights into the mental states and processes of those in the entrepreneurial context. While it provides somewhat unique access into such phenomena, as we explain in the remainder of this article, it still relies on the researchers' interpretation, technical specifications, and an overall understanding of the working mechanisms of cognition and the brain. Second, when it comes to using functional neuroimaging in entrepreneurship research, the majority of entrepreneurship scholars are likely to face significant challenges when adopting, understanding, and evaluating insights coming from this approach. This issue is largely due to the features and limitations of the neuroscience methods, as well as the existence of disciplinary inclinations that may not easily translate from one domain to the other.[3]

Neuroscience as a whole is a complex and evolving field, which may prove paralyzing for those who are interested in the topic but do not yet possess the depth of training needed to design and/or evaluate such research. While the current methodological discussions about neuroscience available in the entrepreneurship and management literature are split between introductory

[3]For example, when neuroscientists refer to a certain neural site "mapping" a certain function—say, the nucleus accumbens (NA) as the "reward center" of the brain—they generally recognize that the activity of the region is not indicative of the absolute level of reward per se but that other factors, like hormonal fluctuations, may vastly contribute to this activation. This evidence, if overlooked, may allow for the emergence of research biases. In other words, if a scholar was to interpret the NA as the brain site for reward in entrepreneurs, without a fuller domain knowledge of the neurobiology of reward (e.g., Daw & Doya, 2006), any deriving insight would likely be impartial and/or inaccurate.

works (e.g., Massaro, 2016; McMullen et al., 2014) and high-end technical readings (see Murray & Antonakis, 2019), a balanced perspective that can concretely mobilize entrepreneurship research questions into neuroscience-based projects is currently missing. Additionally, when submitting research to entrepreneurship journals, researchers proficient in neuroscience often face the challenge of needing to oversimplify certain aspects of their work to accommodate reviewing teams that may have limited knowledge of neuroscience. Thus, we believe there is a compelling need for work that enables the academic entrepreneurship community as a whole to better recognize and understand the potential of functional neuroimaging, clarifies the types of questions that its methods are suited to answer, and paves a constructive path through which scholars might go about conducting neuroscience research in entrepreneurship.

Specifically, we believe that entrepreneurship scholars interested in incorporating a functional neuroimaging approach into their research would benefit from becoming familiar with the following elements: (a) understanding the design principles of neuroscience experiments that correctly probe the question of interest; (b) interpreting the results and their limits in terms of addressing underlying mental processes; (c) appropriately communicating findings, thus avoiding disseminating potentially misleading interpretations; and (d) appreciating what questions can or cannot be answered by combining data from neuroscience and other methods generally used in entrepreneurship research. Thus, our goal is to contribute an accessible and concrete roadmap to develop such knowledge by specifying the theoretical and methodological horizon that entrepreneurship researchers should consider when utilizing functional neuroimaging.

With the aim of accelerating this learning curve, we detail the value of adopting neuroscience in the domain of entrepreneurial cognition. In the next section of the article, we explore why and how the application of neuroimaging and its methods in entrepreneurial cognition can be both useful and relevant. Specifically, we put forward an informed perspective of what a scholar may achieve by "mapping" neural systems that are likely to be salient for topics in entrepreneurship and illustrate several related examples. Next, we provide concrete guidelines on the applications and limitations of two of the most used brain-imaging methods in entrepreneurship research (e.g., Ward et al., 2017): functional Magnetic Resonance Imaging (fMRI) and EEG. Finally, we discuss the implications for research at the intersection of neuroscience and entrepreneurship, as well as impending challenges and related solutions.

The added value of neuroimaging for entrepreneurial cognition

Decisions made in the entrepreneurial context have a significant impact on whether or not new ideas are pursued further. Given the magnitude and importance of such decisions, researchers have long probed why and in what ways individuals conceive of and develop new concepts and thoughts (Choi & Shepherd, 2004), connect previously unconnected dots to form novel views (R. A. Baron, 2006), and reason through strategic decisions (Busenitz & Barney, 1997). Across these areas, a common research pursuit is to improve knowledge of the aspects and roles of cognition in entrepreneurial processes and settings, often referred to as *entrepreneurial cognition* (Baron & Ward, 2004; Grégoire et al., 2011; R. K. Mitchell et al., 2002; Mitchell et al., 2014; Shepherd & Zacharakis, 2002; Shepherd et al., 2015; Wood et al., 2012). In line with this research endeavor, there has been growing interest in understanding entrepreneurs' differences in their desire for achievement, the way they view risk, their need for control, and lack of conformity, among other factors (e.g., De Clercq & Voronov, 2009; Hmieleski & Baron, 2009). Furthermore, inquiry into the emergence of entrepreneurial opportunities and understanding why and how they are recognized and exploited has become central to the field (McMullen & Shepherd, 2006; Shane, 2000).

To date, in studying entrepreneurial cognition, scholars have utilized a variety of methodological approaches such as self-report survey data (MacMillan et al., 1987), experiments (Autio et al., 2013; Murnieks et al., 2011), use of secondary data (Allison et al., 2013), and qualitative techniques (Guler, 2007; Mathias et al., 2015). Together, these approaches have been beneficial for drawing inferences from attributes of observable actions and retrospective recollection. Yet the inferences made from such approaches remain somewhat idiosyncratic in that they are constrained by self-report bias and therefore may fail to fully capture the "true" thoughts and feelings of participants.

Comparatively, functional brain imaging allows researchers to probe further the mental processes occurring within the entrepreneurial setting as they unfold in the brain. The type of information that methods like EEG and fMRI provide take the form of quantifiable, continuous data related to physiological substrates underlining certain mental processes; these data are less prone to participant bias because they are generally measured beyond the participants' direct awareness of the target mental process (Massaro, 2016). At the same time, however, the insight gathered via neuroimaging methods is not always fully objective (e.g., Botvinik-Nezer et al., 2019), given that, as we shall discuss, it often suffers from technical limitations and challenges in terms of interpretation. Thus, we believe that a research strategy that focuses on the methods and data coming from both fields—neuroscience and entrepreneurship—is the path that is most likely to provide a triangulated and comprehensive understanding of entrepreneurial cognition.

This joint approach carries a number of fundamental benefits for research, such as allowing for traditional investigation of entrepreneurial cognition and behavior vis-à-vis neurophysiological cues, their timing, and their drivers and suppressors, involving both discrete brain regions and wider neural networks.[4] Moreover, one clear means in which neuroscience can add to the field of entrepreneurship is by providing information regarding the association between a given physiological activity and specific functional patterns. This knowledge can assist researchers to better appreciate the architecture of human cognitive processing—one of the key end goals of the broader field of cognitive sciences, including of the entrepreneurial cognition paradigm (Dew & Sarasvathy, 2007; Frederiks et al., 2019; Witt, 2000). In other words, neuroimaging can help advance the comprehension of mental processes comprising entrepreneurial thought and action because it can allow researchers to assess whether there is a direct overlap of certain cognitive functions with certain brain systems (and vice versa). It follows that neuroimaging can clarify the extent of integration between the “building blocks” of a cognitive process across different situations (e.g., different tasks, stimuli, or behaviors). For example, a researcher may use neuroimaging to infer whether two individuals share similar cognitive processes upon engaging in the same collaborative task (yet, see also Poldrack, 2006, for the perils of reverse inference versus Hutzler, 2014 and Poldrack, 2011, on the benefits of coexistence of activation).

Applications to entrepreneurship research

With functional neuroimaging, it is possible to investigate similar as well distinct patterns of brain activation under given experimental conditions. Thus, complementing the existing use of experiments in the field of entrepreneurship with neural data can readily allow researchers to take a more fruitful angle of inquiry. That is, researchers may extend current or prospective experimental findings to evaluate what kind of convergent or divergent insight neural data may offer to advance knowledge in entrepreneurial cognition. To better illustrate this opportunity, let us present some key examples.

A longstanding question within the entrepreneurship literature is what distinguishes entrepreneurs from others. While many factors have been considered in the literature thus far, it is generally acknowledged or implied that entrepreneurs, at least to some degree, have a different way of thinking from others (Busenitz & Barney, 1997; McGrath et al., 1992; Nicolaou & Shane, 2009). Addressing this important research query using a neuroscience-based paradigm offers the possibility of confirming (or disconfirming) if neural data can explain such differences. In other words, if thinking and cognition differ between and across entrepreneurs and nonentrepreneurs, it would be possible in principle to assess variations in their respective neural activities.

[4]For instance, the so-called resting state connectivity fMRI approach allows correlations of spontaneous signal variations in subjects at rest with the neural activity of distantly localized brain areas, offering the opportunity to explore the unfolding functional configuration of the human brain as a whole (Van Den Heuvel & Pol, 2010).

Thus, researchers might examine a wealth of features that generally define entrepreneurs or compare them with others: from decision biases, to recognizing opportunities, to the role that individual and collective emotions play alongside cognition or rational thinking. Thus, undertaking a neuroscience approach holds the promise to advance scholarly conversations on why certain individuals may be more prone to engage in entrepreneurial action than others or why some are more successful than others. For example, by assessing simulated entrepreneurial opportunities as part of an experimental design (e.g., Grégoire et al., 2010; Wood et al., 2017), neuroimaging allows us to further assess differential activation in brain systems associated with emotional versus analytical processes—both assumed vital to the process.

Moreover, the analysis of entrepreneurial risk taking is already providing a fertile ground for neuroscience-based research. As Shaver et al. (2017) argue, neuroimaging could be useful in supporting a conceptual analysis and operationalization that allows researchers to distinguish between how risk perceptions can vary with regard to a focal referent (e.g., wealth, time, or opportunity cost). Altogether, having access to the examination of neural patterns of activity could help inform the extent to which cognition unfolds in entrepreneurs and varies with respect to that of nonentrepreneurs, as well as foster knowledge on various decision-making processes. Thus, such pursuits hold potential to advance our understanding of why and how some individuals act more entrepreneurial than others.

Another valuable yet often overlooked use of neuroimaging in entrepreneurship research involves the ability to use neuroscience data to generate predictive models able to develop novel theories, refute existing ones, or reconcile differences between opposing findings. In other words, one can speculate that—as has already emerged in fields such as neuroeconomics (e.g., Loewenstein et al., 2008)—in entrepreneurship, researchers could use the *brain as a predictor*. That is, by measuring neural signals, researchers can use such data to test models and forecast behavioral outcomes (e.g., Genevsky & Knutson, 2015). The power of such forecasting rests on the ability to scale brain-imaging research to large populations: By leveraging small samples, neuroimaging can detect cognitive processing unfolding in the brain and link it to predictions of the future behavior of a larger group or team of individuals (Knutson & Genevsky, 2018). As an example, researchers have found that the so-called reward network of the brain—involving areas such as the nucleus accumbens and the orbitofrontal cortex among others (e.g., Daw & Doya, 2006)—can predict cultural popularity or even the commercial success of songs (while, interestingly, subjective likability was not a predictor; Berns & Moore, 2012). Entrepreneurship researchers might consider building on this line of inquiry. For instance, one could examine whether neural data associated with certain decision processes of a group of crowdfunding investors could inform how a broader population might respond. That is, instead of relying on traditional subjective feedback (e.g., the lean start-up method), by piloting different pitch or product iterations, assessments of brain signals could offer both innovative and scalable, "observable" data. Just as the commercial success of a song can be partly predicted by observing certain neural patterns, entrepreneurship researchers might thus harness the brain as a predictor to forge new knowledge on topics such as the preferences of customers or investors.

Overall, these examples help researchers to further recognize the potential of using neuroimaging to contribute to the empirical advancement of the study of entrepreneurial cognition, as well as the theory building of its conceptual underpinnings. Toward helping scholars interested in integrating neuroscience and entrepreneurial cognition in their research, we propose additional guidance in Table 1. Here, we delineate several research questions in entrepreneurial cognition and pinpoint acknowledged target neural systems and sites that researchers might consider in developing their projects. The broader goal is to illustrate the type of applications that are possible and useful, thereby leading researchers to formulate their own creative applications and use.

Methods of neuroimaging for entrepreneurial cognition

In addition to understanding its theory-building potential, the value of neuroscience in the field of entrepreneurship naturally requires an understanding of the methods themselves. Several neuroscience methods are available to entrepreneurship researchers and have been partly reviewed elsewhere (e.g., Massaro, 2016; Murray & Antonakis, 2019). Here, we advance these early reports by focusing on a pragmatic, actionable methodological coverage of fMRI and EEG to advance the academic conversation in entrepreneurial cognition. We narrow our analysis on these two methods because the few neuroimaging studies that have appeared in the entrepreneurship literature thus far have almost entirely relied on EEG and fMRI, thus making them the likeliest to be exposed to a critical mass of readers (e.g., Lathi et al. 2018; Shane et al., 2020). Moreover, they both specifically assess the brain, which is not only our "thinking organ" but is also responsible for directly processing information toward action and decisionmaking and as such is of immediate relevance to the paradigm of entrepreneurial cognition. Finally, these approaches are particularly apt for safely assessing brain activity as it unfolds and can empirically model and theorize dynamic aspects of cognition and how the brain learns, adapts, and even changes within the entrepreneurship setting. Table 2 offers further practical guidance when considering neuroimaging research.

Table 1. Examples of functions and related neural systems that can be used to glean new insights within entrepreneurship research.

Cognitive Function	Target Neural System/ Site	Main Methodology	Illustrative Linkages to Entrepreneurship Research
Saliency of fear/alarming stimuli (i.e., fearful content rapid processing)	Amygdala activation	fMRI	Providing quantifiable novel insights about the differential role of fear and fear of failure across different types of individuals in the entrepreneurial context (Morgan & Sisak, 2016; Wennberg et al., 2013).
Reward processing and anticipation	Nucleus accumbens activation	fMRI	Extending knowledge on predictive drivers of opportunity evaluation, such as the role of anticipated monetary versus social gains (Zahra et al., 2009)
Attention	Occipital alpha band increase	EEG	Complementing research on entrepreneurial alertness and opportunity recognition (Busenitz, 1996; Haynie et al., 2009; Tang et al., 2012).
Emotion (positive/negative)	Frontal alpha band left/ right asymmetry	EEG	Advancing knowledge of the distinct roles of emotion vs. cognition in entrepreneurial decision making (Cardon et al., 2012; Foo, 2011; Keh et al., 2002)
Dispositions/Traits	Rostral anterior cingulate cortex activation	fMRI	Fostering understanding of the pervasiveness and role of trait optimism across entrepreneurs (Dushnitsky, 2010; Hmieleski & Baron, 2009).
Working memory	Frontal theta band activity	EEG	Detailed mapping of variation in polychronicity, temporal depths, and multitasking in entrepreneurs (Bluedorn & Martin, 2008).
Memory (specific: register/consolidate)	Hippocampus activation	fMRI	Providing differential evidence on the neurophysiological substrates supporting counterfactual thinking in entrepreneurs vs. nonentrepreneurs (Arora et al., 2013; Baron, 2000; Gaglio, 2004).
Rational decision making	Prefrontal cortex activation	EEG/fMRI	Appreciating the presence, severity, and unfolding of biases in entrepreneurial decision-making tasks (Busenitz & Barney, 1997; Shepherd et al., 2015).
Pain (including emotional exclusion or "pain of paying")	Insula activation	fMRI	Exploring individual differences in resilience and grit (Bullough et al., 2014; Mueller et al., 2017).

Table 2. Possible issues to consider when planning and conducting a successful neuroimaging project in entrepreneurial cognition.

1. Am I asking a research question about mental processes that may be involved in entrepreneurial cognition?
2. Is there preexisting neuroscience research broadly related to the target mental process?
3. Am I asking a research question that has supporting behavioral evidence? If not, have/will I collect supporting behavioral data (e.g., studies 1/2 or within the neuroimaging study)?
4. Have I established a team of both entrepreneurship researchers and neuroscientists fully committed to delivering this project?
5. Have I secured funding and planned a detailed research strategy (from ethical approval and data collection to data retention) and publication pipeline?
6. Have I formulated hypotheses fully testable with neuroimaging methods?
7. Have I designed an experimental task that is a "faithful" representation of the entrepreneurial process under investigation?
8. Is there a baseline/control in my research design?
9. If my analytical design requires so, can I support my sample size with statistical power analysis or by leveraging a narrative using comparable theories/experiments/sampling/references?
10. Have I engaged in preprocessing and postprocessing analyses (e.g., multiple comparisons) following state-of-the-art guidelines in neuroimaging?
11. In framing my contribution, am I making correct claims of causality?
12. Am I reporting the full methodological details, benefits, and limitations of neuroimaging findings?

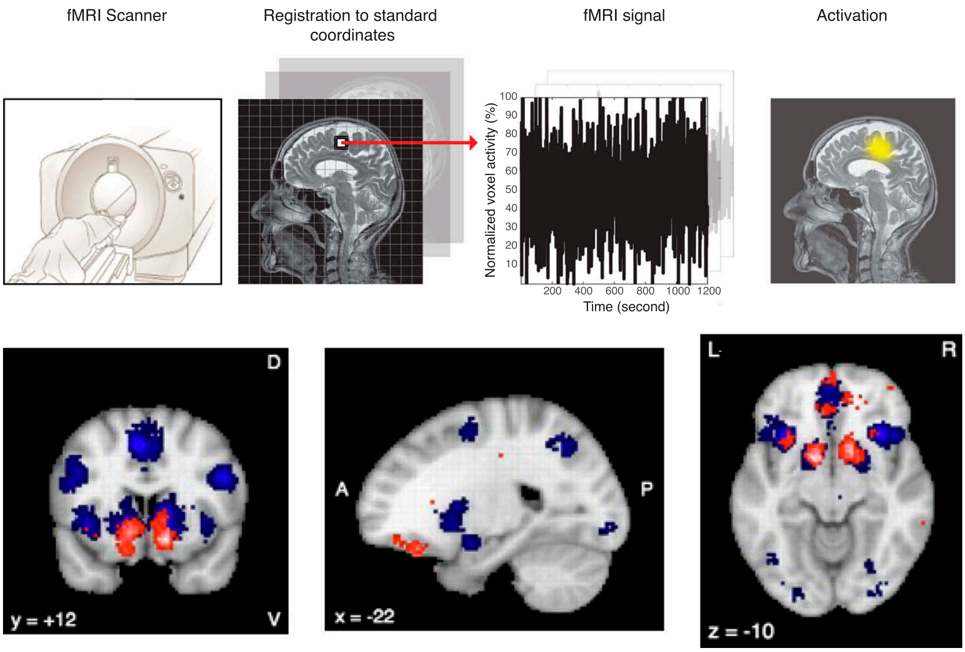

Figure 1. Upper Panel: fMRI in Use. Illustration of an fMRI scanner (left). The data from multiple 3-dimensional volumetric pixels ('Voxels') are registered to a standard coordinates to align the brain (second from left). Following, the signal from each voxel is normalized and aligned. Signals from regions that show significant change in activity are associated with certain functions. Lower Panel: Activation peaks (red = association test; blue = uniformity test) of brain sites conventionally associated with decision-making; these panels were obtained by performing a meta-analysis (based on the framework developed by Yarkoni et al., 2011) of 509 fMRI activation studies, published between 1992 and 2020, that reported "decision making" as a keyword.

Functional Magnetic Resonance Imaging (fMRI)

Functional magnetic resonance imaging (fMRI) measures brain activity by capturing changes associated with blood flow in the brain (Logothetis et al., 2001; Ogawa et al., 1990). As illustrated in Figure 1, fMRI does not directly measure neurons' activity per se but relies on variations of the signal associated with the level of oxygenated blood in a given region of the brain (i.e., the so-called activated brain region) relative to other conditions; this signal is called the *Blood-Oxygenated Level Dependent* (BOLD) signal (Ogawa et al., 1990). When a particular brain region is actively engaged in a mental process or activity, the blood flow in the region increases relative to other areas (Zago et al., 2009) so that it can quickly use the nutrients available in the blood at that moment, also turning oxygenated hemoglobin into its deoxygenated form. In response to increased activity, the BOLD signal shows a hemodynamic response function (HRF), which largely remains constant in the same brain region of a participant but varies between participants and across different brain regions (Aguirre et al., 1998). Thus, as subjects engage in tasks, dynamic maps of moment-to-moment brain activity can be modeled.

fMRI research is performed with a MR scanner, a large magnet capable of generating a magnetic field (where strength is measured in Tesla, T) several thousand times stronger than the Earth's magnetic field. During a fMRI measurement, a participant lies inside the bore of the magnet, and the magnetic field is applied constantly across the brain, while the subject is either resting or performing a task. The signals are then processed through a series of analytical steps, and fMRI images are constructed according to voxels: 3D pixels carrying volumetric information on the brain. Hence, the spatial resolution of fMRI depends on the size of the voxel, usually around 1 mm x 1 mm x 1 mm (i.e., 1 mm^3). Using fMRI, there is a delay in temporal resolution, where blood flow to certain brain regions is lagged by a few seconds after those areas have been activated. fMRI can produce a reading of the entire brain and/or a high-density image of specific portions, including structures located deep inside the brain. Therefore, fMRI can yield indicators of neural responses in sites that are located below the cortex.

Blocked and event-related designs

Due to physiological noise in the BOLD signal, multiple repetitions of stimuli per experimental conditions are required to gain sufficient power and reliability in a fMRI study. Two main categories exist: block and event-related designs (see, for review, Amaro & Barker, 2006). In the block design, which generally allows researchers to achieve high statistical power, multiple stimulus repetitions that fit the same experimental condition are grouped together. Each block lasts around 20–40 seconds, accounting for blood flow decay, and there is a minimum of two to four blocks per condition: the more repetitions, the more reliable the signal. In the event-related case, different stimuli or conditions can instead be spread during data analysis (Josephs et al., 1999). Mixed (blocked and event-related) designs are also popular avenues (Donaldson, 2004).

Experimental strategies

One of the most common ways to design a task for a fMRI experiment is that of cognitive subtraction, which compares the activity in different brain regions in response to a given task (Friston et al., 1996). This design compares two brain states that are believed to differ in the independent variable only. The approach relies on the concept of "pure insertion," that is, the notion that a cognitive process can be inserted into a task without affecting other processes and that there are no interactions between the cognitive components of a task. For this reason, the choice of a baseline is crucial (Logothetis, 2008).

Another method is that of cognitive conjunction, which allows assessing activated brain sites that are shared across different stages of a cognitive process (Price & Friston, 1997). Typically, studies are designed so that two or more distinct tasks share one common processing difference. The correlates of the mental process of interest are then associated with the common areas of activation for each task pair. This approach does not depend on pure insertion and offers more flexibility in the choice of the baseline.

In a parametric design, the variable of interest is considered as a continuous dimension, which essentially means it has infinite possible values (Friston et al., 1996). This approach measures associations between brain activity and changes in the variable of interest rather than variances in brain activity between conditions as in the other designs. This design allows for employing computational models that can provide answers weighting neural representations of behavior and ultimately explain the "so what?" of a study (i.e., when, why, or how a mental process takes place).

Finally, functional integration models show how different brain regions' activities influence each other (Van Den Heuvel & Pol, 2010). The method allows for inference of the effective or functional connectivity between brain regions during a task. This networked approach usually relies on principal component analysis to reveal the overall variance between groups. Recently, functional integration studies have been designed without a predefined experimental task. These are known as resting-state paradigms, and participants are asked to lie back in the scanner and rest while fluctuations in brain activity are measured (De Luca et al., 2006). The functional integration approach may offer particularly promising applications for entrepreneurship. For instance, research on resting-state fMRI has recently allowed researchers to define the so-called Default Mode Network (DMN), which is a distinctive network of brain regions whose activities are highly correlated with one another (Buckner et al., 2008). Functional integration has shown that the DMN can also be associated with aspects such as social cognition (Raichle & Snyder, 2007) and recall of experiences resonant (versus dissonant) with leaders (Boyatzis et al., 2012; see also Boyatzis, Rochford, & Jack, 2014 for the dynamics between DMN and the inhibiting task-positive network in leadership research).

fMRI data analysis

fMRI data requires complex pre- and postprocessing steps performed with dedicated algorithms and procedures. The main steps are the slice timing correction (Sladky et al., 2011) and the correction for head movement, which, if not addressed, can result in a given site being more difficult to detect or in a false-positive.

Stereotactic normalization, which involves mapping regions of the brain onto a reference, is another important data processing stage (Thirion et al., 2006). This involves dividing the brain into thousands to millions of voxels, each with specific spatial coordinates that can be mapped similarly across the brains of the different study participants for comparison. Mathematical transformations are applied to each image to fit a standard space, generally provided by the atlas of Talairach and Tournoux (1988).

Finally, smoothing improves the signal-to-noise ratio, and this is an advantage for analyzing groups of subjects. However, it also raises the spatial extent of active regions by "spreading" the activation signal to neighboring inactive voxels, increasing the chance of finding common regions of activity because the procedure involves averaging the activity between subjects. Fortunately for novice neuroimagers, such data can be examined through the use of dedicated software, such as SPM (Brett et al., 2002) or FSL (Jenkinson et al. 2012).

Strengths and weaknesses

fMRI has been one of the most influential and versatile neuroimaging tools used to date (e.g., Kable, 2011; Loued-Khenissi et al., 2019). fMRI has clear benefits over other methods, such as higher spatial reading. In this way, researchers may identify a priori given regions of interest (ROIs) of the brain on which to test their hypotheses (see also Table 1). However, fMRI comes with low temporal resolution (cf. EEG), which limits the opportunity to understand the temporal dynamics of cognitive events at the neuronal level (i.e., in fMRI, the timing of the event is related to the HRF, which is delayed compared to the neurons' electrical firing).

There are several caveats to consider when evaluating the use of this technique. First, the cost of a MRI machine regularly exceeds US$1 million, making it impractical (and unnecessary) for business schools or practitioners to have in-house; relatedly, the costs of a fMRI experiment typically range between US$500 and US$1,000 per session (e.g., 1 hour/subject). Next, the physics of the technique does not allow it to be performed outside the MR suite, and there is a general assumption of linearity between the BOLD signal and the baseline activity, suggesting that the technique is not well suited for the investigation of long-term changes in neural activity. Finally, fMRI results typically yield thousands to millions of voxels, suggesting that—at random—a certain number of voxels may spuriously correlate with behavior. Ironically, Bennet et al. (2009) won the Ig Nobel Prize, demonstrating that even a dead salmon, when "shown" images of people in social situations, can display patterns of neural activations. This issue alerts us that if fMRI analysis does not correct for multiple comparisons, then any fMRI study can potentially find a brain region that spuriously correlates with a behavior.[5] Most importantly, these considerations remind us that, regardless of the tool a researcher uses, it is fundamental to ensure that each strategy is well aligned to the research question and hypotheses being tested (Massaro, 2016).

Recent methodological advancements

Methodological research in fMRI is vibrant and rapidly expanding. Here, we discuss two recent avenues that may benefit entrepreneurship research moving forward. The first is functional laminar fMRI, the functional imaging of human cortical layers (Lawrence et al., 2019) that builds on methods to derive insights from the activity of neurons in deeper layers of the brain (Mormann et al., 2017). Recent developments have allowed researchers to identify that both feedforward and feedback responses can be dissociated by their laminar profiles, in vivo, leading to several applications in cognitive research on a variety of topics relevant to entrepreneurial cognition, such as working memory and selective attention (Lawrence et al., 2019).

The second avenue is that of multivoxel pattern analysis (MVPA), a machine learning technique used to investigate information contained in "networked" distributed patterns of neural activity to infer the functional role of brain areas and their connections (Mahmoudi et al., 2012; Norman et al., 2006). MPVA is a favorable method for investigating networked neural activities without requiring researchers to define a priori computational models or narrow their focus on only a few regions of interests. MPVA is useful to interpret overlapping functional activations and allows increased sensitivity in the detection of cognitive states, thus holding the ability to correlate neural data (i.e., classifier estimates) with behavioral measures across trials, further supporting the promise of refining explanations of entrepreneurial cognition and behavior on the basis of neural data (Peelen & Downing, 2007).

[5]That is, if one measures the change in activity of, say, 5 million voxels (which is the order of magnitude of the number of timeseries generated in a fMRI session) and correlate those, individually, to a behavior (i.e., the blinking of an eye by the subject), we are likely to find, by chance, at least one voxel that correlates with the eye batting. If we do not estimate the probability of finding such a correlation—by dividing the probability value by the number of options (practically, instead of significant result being coded at a p value of, say, .01, it would now be expected at .01/5,000,000 = .000000002 to be considered significant)—we risk incorrectly suggesting that two random events may be seen as causal (for further explanation, see Cerf et al., 2017).

Finally, a third promising avenue is that of miniaturized fMRI, a version of the robust magnetic device occupying much less physical space (in the order of an EEG headset). This setup is not a commercial option yet; however, growing funding for tech ventures that aim to develop such a device suggests that it might become the next reality in neuroimaging. It goes without saying that if such a device is fully developed and comes to market, some of the intrinsic disadvantages of fMRI would be mitigated, and this would afford a new set of opportunities for field research.

Electroencephalography

EEG has been utilized in neuroscience research for decades (Berger, 1924; Tivadar & Murray, 2019). As illustrated in Figure 2, it is a noninvasive technique that records the electrical activity of the brain by using electrodes positioned on a subject's scalp. Specifically, EEG assesses the synchrony of voltage fluctuations resulting from the ionic currents within groups of neurons aligned in parallel. By measuring the residual fluctuations of these currents, researchers can have subjects engage in a wide range of tasks while observing the electrical activity that stems from brain regions of interest. However, because EEG allows recording only from brain areas in which neurons are organized in parallel, it is difficult to directly assess brain structures located below its outer (i.e., cortical) layer. Nonetheless, EEG is well suited for recording cortical activity, and it has excellent temporal resolution (i.e., typical neuron bursts are at the order of milliseconds), making it exceptionally suited to capturing the timing of mental processes (Sutton et al., 1965).

A standard EEG apparatus uses a multichannel amplifier connected to several conductive electrodes (up to 128 or more in high-density devices)

Figure 2. EEG in use (left panel) and EEG electrodes reference (termed 'Montage') on a subject's head, from above.

placed on the subject's head and usually inserted in a wearable head cap. It often takes up to 30 minutes to prepare the setup because it requires the precise placement of the electrodes and the use of conductive gels or solutions. The electrodes must be placed at various sites on the scalp, which are usually described with reference to the International 10–20 System (see Klem et al., 1999 for a seminal review). The electrodes are labeled with a letter, indicating their anatomical locations (C = central; F = frontal; O = occipital; P = parietal; T = temporal), and a number indicating the hemisphere (even numbers are used for recordings from the right hemisphere, odd numbers for the left hemisphere, while *z* labels the midline). The acquired signals are digitized onto a computer, processed, and analyzed.

Frequency analyses

An EEG records spikes and waves in the electrical activity of the brain, which oscillate at different rates (i.e., frequencies). Standard frequency waves that are correlated with specific behaviors are named. The most commonly used in research (see Figure 3) include alpha waves, with oscillations in the 7–13 Hz range; beta waves, in the 13–20 Hz range; and gamma waves, in the 20 Hz and above range. Delta and theta waves are in the 1–4 Hz and 1–8 Hz ranges respectively.

While these frequencies naturally occur, several efforts have been made to link patterns of oscillations to distinctive cognitive functions (Başar et al., 2001). For example, alpha waves, at the back of one's brain, are often associated with increased visual attention during a task. Yet, due to low specificity and the traditional reliance on visual analyses of the waveforms, early attempts at mapping a frequency band with a particular cognitive process have also often been imprecise (as reported in Harmon-Jones & Peterson, 2009). More recently, the increased use of spectral power analyses has offered more robust approaches (e.g., Fitzgibbon et al., 2004).

Event-Related Potentials (ERPs)

A common index of brain activity that relates to EEG signals is event-related potentials or ERPs. ERPs refer to averaged EEG responses that are the direct result of a specific cognitive event or stimulus (Teplan, 2002). When an EEG is recorded during an experimental task involving specific events, it is possible to examine the EEG periods (epochs) that expose neural processes distinctively associated with these occurrences. The use of ERPs is a reliable method to study the neurophysiological correlates of cognitive activity associated with information processing (Handy, 2005). However, it requires a significant number of repeated trials to be able to average the signal from noisy fluctuations that often occur spontaneously.

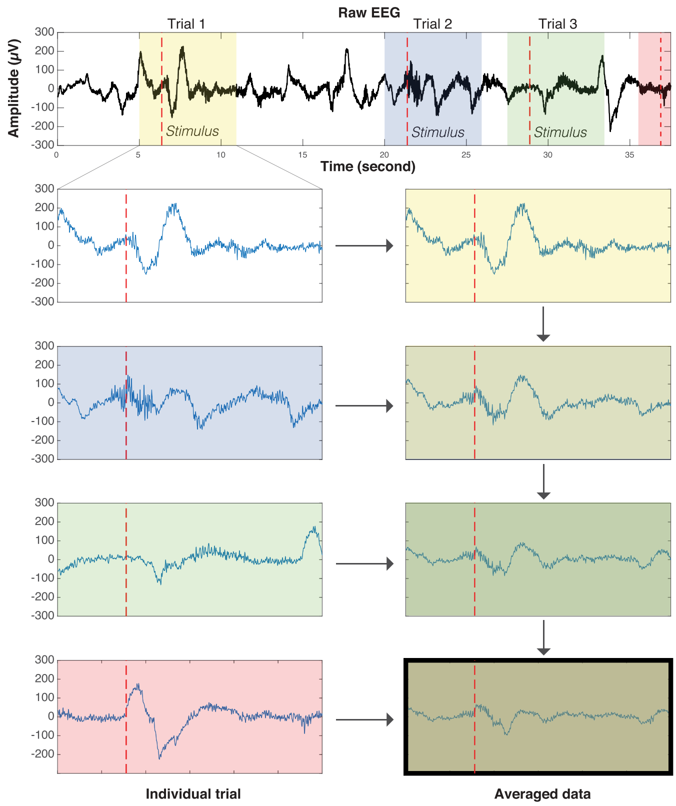

Figure 3. Raw EEG data (top) is segmented in alignment with stimuli presentation (shaded area highlights the segments corresponding to each trial; dashed line marks a stimulus onset within each trial). The segments are shown on the left. Averaging all the segments (right) shows the Evoked Potential, which highlights the neural response to the stimulus.

The signals are displayed by plotting time on the *x*-axis and the potential of the electrode on the *y*-axis. The resulting chart consists of a sequence of peaks for each electrode, each with a fairly different outline. The peaks are identified with either “P” (positive) or “N” (negative) and are numbered. For instance, N1, N2, and N3 denote the first, second, and third negative peaks respectively. They can also be marked with the timing of the peak (i.e., P300 indicates a positive peak at 300 milliseconds). It is worth noting that the polarity of a peak has little meaning in cognitive terms, nor does a positive peak reflect excitation and a negative peak inhibition.

Importantly, the characteristic peaks and troughs of the ERP waveform can be linked to cognition by assessing timing, latency, and the amplitude of the peaks (e.g., Polich & Kok, 1995). For example, repeatedly showing subjects images of faces versus objects, and then averaging the neural activity at the onset of a face image, often yields a consistent increase in EEG readings at the 300-millisecond mark (P300) in temporal electrodes.

Strengths and weaknesses

EEG offers several benefits to cognitive research in entrepreneurship. The costs are generally contained; they are in the range of US$200 per subject, and an initial investment in equipment starts at approximately US$20,000. Moreover, the method is silent and does not generate any potentially distracting noise and is more portable than other approaches, allowing for greater flexibility in the data collection setting. In terms of research design, EEG and ERPs studies can be conducted with relatively simple paradigms. Moreover, EEG has excellent temporal resolution, which makes it feasible to link to neural processes in the brain. Finally, in contrast to BOLD fMRI that reveals a correlate of the neural signal (i.e., oxygenated blood accumulated by neurons that, potentially, facilitate neural "firing"), EEG relies on a signal that is directly neural (i.e., groups of neurons firing). Therefore, the mechanisms by which the brain elicits the response measured by EEG are well understood, making their interpretation somewhat simpler than that of other methods. Notwithstanding these benefits, there are some important limitations, including many of the processing issues already discussed for fMRI—namely, low spatial resolution, challenges in detecting inner brain region activity, a poor signal-to-noise ratio, and a lengthy setup time.

Recent methodological advancements

Recently, several new EEG-based research approaches have emerged. In leadership research, for example, quantitative EEG (qEEG) has been used in an increasing number of applications (Massaro, 2015; Waldman et al., 2017). Indeed, while EEG frequency analyses cannot provide direct information on the anatomical origins of signals, qEEG offers topographic display and analysis of brain electrophysiological data by leveraging on transformation of the EEG signal. Likewise, technological advancements allow the use of dry sensors for data acquisition. Dry sensors do not require any gel to be placed between the scalp and the electrode for reduced noise, thus allowing both increased accessibility and reduction in the calibration time. Moreover, a recent trend in neuroscience tools is to offer wireless portability, therefore allowing for the exploration of neural activities in unprecedented contexts and situations (e.g., group/team interactions or acquisition during movement; see Barnett & Cerf, 2017; Einhauser et al., 2009).

Challenges and solutions in using neuroimaging

We are optimistic that our comprehensive analysis conveys the benefits of using neuroimaging in entrepreneurial research. Nonetheless, as we have already alluded, there are several challenges in the practical implementation of the insights that we have presented here. To address some of these concerns, we now pinpoint some of the most frequent challenges that entrepreneurship scholars might encounter when embarking on neuroscience research and offer some possible solutions. Moreover, to provide practical and actionable insights, we have integrated these points and the principles presented throughout this article in a checklist aimed at effectively moving a neuro-entrepreneurship research project from the idea stage to implementation.

Research cultures and dynamics

The most apparent issues for entrepreneurship scholars seeking to conduct neuroimaging research involve the cross-disciplinary nature of the work, the disparate knowledge foundations, and the asymmetrical systems of incentives for neuroscience and entrepreneurship scholars. Authorship teams with both social neuroscientists and entrepreneurship researchers represent the starting point needed to conduct effective neuro-entrepreneurship research. Yet a number of challenges may arise when performing empirical projects, ranging from the cost sharing involved to differences in cultural systems. Thus, establishing mechanisms for splitting costs across institutions and scoping for opportunities to secure external funding are all important considerations before starting a project and will help to ensure successful deliverables. Moreover, conducting pilot tests, which are often preconditions for accessing research funding, or using more economical imaging approaches (e.g., EEG-based studies to support fMRI ones) can be useful to capture valuable insights into the manipulated conditions and protocols used, as well as to facilitate dialogue between research parties.

Another apparent challenge is related to the disparate knowledge base between neuroscientists and entrepreneurship scholars. An open mindset and ongoing two-way communication are vital for enabling refinement and bolstering shared knowledge. Still, much as entrepreneurship scholars may not accrue meaningful external rewards from a publication in a neuroscience journal, neuroscientists may not accrue significant rewards from publishing in business journals. Thus, we believe that envisioning multiple publication trajectories up front—in both neuroscience and business journals—will be the most appealing reward mechanism to satisfy the goals of both parties. Yet such an avenue is not without challenges. The requirements for publication in a journal, level of methodological rigor needed, depth of theoretical insights expected, different style of writing, and reviewing times all vary between the fields and contribute to the difficulty of bridging gaps between them. Thus, we believe that only if researchers from both sides, as well as their institutions and related academic journals, embrace each other's different cultural norms and practices will this interdisciplinary avenue flourish in the future.

External and ecological validity

Neuroimaging research is regularly conducted in controlled laboratory settings, yet it is unable to fully replicate real-world "entrepreneurial scenarios," given that exogenous and confounding factors (e.g., sounds, visual stimuli, movement) can introduce noise in the recording of data. Some studies might thus face criticism of drifting too far from the "natural setting" sought after in entrepreneurship. We offer two recommendations in response to such concerns. First, pursuing appropriate research questions and tasks is vital; in other words, certain neuro-entrepreneurship tasks will be more generally applicable than others. For example, capturing the neural activity of investors compared to a control group as they view manipulated pitch videos can lend good generalizability to a study. Second, including behavioral data collections either within the imaging sessions or in complementary studies (i.e., study 1/study 2) will strengthen the validity of the findings. Not only will this strategy allow for data triangulation, it can also justify the associations found between brain activity and behaviors, thereby bolstering the overall contribution and rigor of a study. Similarly, complementing a neuroscience study with a qualitative study or field experiment may be an innovative idea appealing to entrepreneurship researchers who wish to add further rigor to their research. Finally, encouraging advances are coming from other neuroscience methods, such as eye-tracking, skin conductance, and heart rate variability, which are increasingly allowing for portability outside the laboratory and even wearability (e.g., Barnett & Cerf, 2017; Massaro & Pecchia, 2019).

Sample sizes

Sample sizes in neuroimaging research are usually smaller than those utilized in entrepreneurship experiments. For example, highly cited fMRI studies published in premier scientific journals, such as *Nature* and *Science*, often report samples of around 20 subjects, if not less (cf. De Martino et al., 2006; Northoff et al., 2007); the same is true for fMRI works in leading business journals (cf. Bruguier et al., 2010; Mason et al., 2009). Yet a study with a small number of subjects should not be seen as a core issue or a reason for rejection. Practically, small sample sizes are often a necessity attributable to the cost and time involved in this kind of research. Moreover, when repeated measures are employed in a study design, where a high volume of trials per condition is used, statistical calculations used to justify a chosen sample size, or newer forms of analysis such as MPVA, may be used as further justification for using small numbers of participants (Desmond & Glover, 2002). Thus, any well-argued, "small" sample size should not be challenged during the peer-review process by default; rather researchers should be encouraged to proactively provide fuller methodological details and contextual explanations. Moreover, the statistical significance of a large number of neuroscience studies is often notably high, despite the low subject count: Researchers compensate for sampling shortages with rigorous methods that can validate the results in ways that ensure greater accuracy and predictability.

Ethical considerations

A final issue worthy of discussion concerns the multiple ethical aspects surrounding the use of neuroimaging in entrepreneurship research. While there has been some initial debate on the topic in the broader field of organizational studies (Jack et al., 2019), fortunately, the neuroscience community has already provided a roadmap to orient and move this conversation forward. Fifteen years ago, a task force of neuroscientists proposed "neuroethics" as a field that "seeks to understand and navigate the ethical tensions and conflicts that arise in the research and application of neuroscientific knowledge and techniques" (Force & Society, 2019; see also Farah, 2005). These ethical struggles exist both in the psychological constructs investigated with neuroimaging (e.g., Cropanzano et al., 2017; Massaro & Becker, 2015) as well as in the use of neuroscience technology in cognitive research (Robertson et al., 2017). The latter is of crucial interest for entrepreneurship research using neuroscience. For instance, the promise of capturing the physiological data of individuals with wearables and web-connected tools has expanded to include indicators of behaviors (Force & Society, 2019). This ability has rapidly generated ethical apprehensions regarding personal autonomy and personal privacy. Thus, as applied to entrepreneurship, we could easily anticipate that the prospect of separating more- versus less-successful entrepreneurs on the basis of patterns of neural activity might be attractive to venture capitalists and investors, while also raising important ethical issues.

Similarly, causal connections between neural data and certain conditions such as attention deficit hyperactivity disorder (ADHD) may lead to significant ethical concerns (Mordre et al., 2011). Given the growing interest in ADHD within the entrepreneurship literature (Wiklund et al., 2017), should research be able to achieve such causative evidence, it could have significant consequences spanning from positive preemptive frameworks to somewhat more worrisome selection interventions.

Even though most of these issues are still far from being of prominent concern in entrepreneurship research, they call for a careful reflection on the postulates of this emerging research area. Moving forward, we believe that the field of entrepreneurship has the opportunity to benefit greatly from existing discussions in neuroethics. Moreover, as entrepreneurship is characterized by a high degree of practical evidence, scholars working in this area will have the opportunity to become active contributors and help address some longstanding ethical concerns or expose novel issues worthy of discussion.

Concluding remarks

In this article, we presented a cross-disciplinary effort to take a step toward bridging entrepreneurship research and functional neuroimaging, arguing that the time is ripe for the progression of a neuroscience-based paradigm for studying entrepreneurial cognitive processes and linkages to action. The opportunity to objectively assess mental processes unfolding in the brain, associate such processes with behavior, and ultimately generate physiologically informed theories of entrepreneurial cognition are the pillars supporting why and how neuroimaging can complement, challenge, and ultimately extend current knowledge in entrepreneurship. It has not escaped our notice that these can also drive novel understandings in neuroscience that currently are under-explored (i.e., the neural underpinnings of creativity in the brain).

Some limitations are associated with this work. First, the nature of this article broadly targets novice scholars, not those few researchers already committed to neuroscience. As such, we did not and could not discuss each and every methodological aspect or research topic that these tools could satisfy. Relatedly, there is not enough material available in the literature to allow a meaningful review of current neuroimaging studies related to entrepreneurship. Nonetheless, we hope that having pinpointed key research examples pertaining to entrepreneurial cognition, our work will promote future research in the form of empirical studies, systematic reviews, and eventually, meta-analytical efforts.

Another limitation is that methodological advancements are rapidly developing in mainstream neuroscience research; therefore, scientific practice is constantly being updated and refined. A corollary is that methodological knowledge can quickly become obsolete or even allow some to question the reliability of what has been done in the past. We attempted to minimize such issues by providing a logical and actionable focus on what is generally considered to be established foundational knowledge in neuroimaging, yet has received little or no exposure to date in leading entrepreneurship outlets. We do, however, believe that any future arguments focusing on the limitations of neuroimaging methods in entrepreneurship will be best assisted by a dialogue, including the potential that such limitations may promote in terms of new directions for research.

In conclusion, we hope that the work presented here will enable functional neuroimaging research to be more accessible to the academic entrepreneurship community as a whole and that our efforts will also serve as a cornerstone for the further growth of empirical investigations and theoretical frameworks in this area.

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