Markets in the Times of Corona: A Cognitive Neuroscience Approach

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Abstract

We're living in exceptional times in many domains. In my realm of financial economics, I see, as has been the case during previous financial crises, the breakdown of the rational expectations and efficient markets paradigms. But this time is different because it just so happens that, just previous to COVID-19 breaking into the scene, I took a course in neuroeconomics – the combination of economics, neuroscience, and psychology used to determine how individuals make economic decisions. This article applies the insights a gained to the exceptionally volatile financial markets we are now experiencing.

Unlike previous financial crises, the COVID-19 crisis resulted not from unsound financial instruments or weak bank balance sheets but, much like a devastating hurricane, from an act of nature. But whatever the differences in origin, fear and greed are the common denominators of disrupted financial markets: the advent of Corona was preceded by an exceptionally long period of unchecked greed, which eventually led to excessive leverage and unsustainable asset-price levels. The inevitable current collapse is the result of unbridled fear, which must subside before any recovery in asset prices is possible.

The cognitive neurosciences help us gain insights into this boom/bust pattern through a deeper understanding of the dynamics of emotion and human behavior.

In this article, I describe some recent research from the neurosciences literature on fear and reward learning, mirror neurons, theory of mind, and the link between emotion and rational behavior. By exploring the neuroscientific basis of cognition and behavior, we may be able to identify the fundamentals of the current financial crisis, and improve our models and methods for dealing with it.

"A pestilence isn't a thing made to man's measure; therefore we tell ourselves that pestilence is a mere bogey of the mind, a bad dream that will pass away."
– Albert Camus

1 Introduction

In March 1933, unemployment in the United States was at an all-time high. Over 4,000 banks had failed during the previous two months. Bread lines stretched around entire blocks in the largest cities. The country was in the grip of the Great Depression. This was the context in which Franklin Delano Roosevelt delivered his first inaugural address to the American people as the 32nd president of the United States. He began his address not by discussing economic conditions, nor by laying out his proposal for the "New Deal" , but with a powerful observation that still resonates today: "So, first of all, let me assert my firm belief that the only thing we have to fear is fear itself – nameless, unreasoning, unjustified terror which paralyzes needed efforts to convert retreat into advance" .

Seventy-five years later, these words have become more relevant than FDR could ever have imagined. The current Corona crisis – is, in essence, all about fear. Since money was invented, fortunes have always been made and lost by intrepid investors, but the current crisis feels different because of the sheer size of potential losses and the apparent randomness of their timing and victims.

From a narrow perspective, a demand shock was the initial flash point of the crisis. However, what makes this shock unique is the sheer uncertainty about its longevity. We all understand the nature of the peril: economic time (i.e., revenue generation) virtually stopped but financial time (i.e. interest accrual) did not even slow down. Deprived of all or part of their income, highly leveraged companies and individuals will become insolvent first but we don't have clear enough of a picture of the persistence of the demand shock to be sure that even financially healthy companies and individuals will not.

But even a cursory review of expansive histories of past crises such as Kindleberger's (1978) classic and Reinhart and Rogoff's (2010) more recent definitive treatise suggests a common origin for all financial bubbles and busts: fear and greed. A period of unchecked greed leads to unsustainable asset-price levels, and the inevitable price decline ushers in a period of unbridled fear. The broader the participation in the growth of the bubble, the deeper the impact on the real economy because of the number of households affected by the bubble's bursting.

The relevance of human behavior to financial markets and economic affairs is not a new idea. John Maynard Keynes (1936) observed over seven decades ago that economic decisions were due more to "animal spirits" than carefully weighed probabilities, and that financial markets operated more like beauty contests than efficient price-discovery platforms. However, despite the early successes of Keynesian macroeconomics, the more recent dominance of the rational expectations school of thought has left little room for animal spirits in the policymaker's toolkit. One of the few positive consequences of the 2007-2009 financial crisis was the realization that our approach approach to measuring and managing systemic risk in the financial system was (and continues to be) inadequate, and that policymakers need a broader intellectual framework.

In this article, I hope to serve that need by exploring the neuroscientific underpinnings of human behavior, particularly those behaviors most relevant to systemic risk. If fear and greed are the key drivers of all financial crises, then a better understanding of how the brain produces these behaviors may eventually allow us to formulate more effective policies to manage their consequences. For example, neuroscientists have shown that monetary gain stimulates the same reward circuitry as cocaine – in both cases, dopamine is released into the nucleus accumbens. Similarly, the threat of financial loss apparently activates the same fight-or-flight response as a physical attack, releasing adrenaline and cortisol into the bloodstream, resulting in elevated heart rate, blood pressure, and alertness. These reactions are hardwired into human physiology, and while we're often able to overcome our biology through education, experience, or genetic good luck during normal market conditions, under more emotionally charged circumstances, the vast majority of the human population will behave in largely predictable ways. This neurophysiological basis for Keynes's animal spirits has important implications for corporations and investors, including the need for path-dependent and adaptive capital requirements and leverage constraints, more accurate and timely measures of systemic risk so market participants can respond appropriately, and more direct feedback loops between policies and outcomes that will enhance our collective intelligence through reinforcement learning.

To develop this cognitive neurosciences perspective of financial crises, I begin in Section 2 with a brief history of our understanding of the brain, which was surprisingly primitive until quite recently. Of course, the brain is extraordinarily complex, so by necessity we have to narrow our focus to just those components that are most relevant for our purposes: fear, greed (or, its close complement, pleasure), risk preferences, rationality, and the various combinations of these elements. In Section 3, I describe fear learning and the amygdala, one of the most important neural components of financial crises. In Section 4, I turn to the neural mechanisms most closely associated with the build-up of bubbles – pleasure and greed – and show how the adaptiveness of neural systems for reward and punishment makes crises virtually unavoidable. This tendency is spelled out more clearly in Section 5, which is devoted to the effects of risk on decision-making, which is predictable and, in the case of rogue traders, often disastrous. Too much emotion can trigger irrational behavior, but so can too little emotion, and in Section 6, I describe a definition of rationality from the neurosciences perspective that's radically different from the economic notion of rational expectations, the difference hinging critically on the unique role of emotion. The mechanisms of Sections 3–6 all refer to individual behavior, but in Section 7, I explore the impact of social interactions through the neurophysiology of mirror neurons, brain cells dedicated to allowing others to "feel your pain". All of these neural components interact to produce intentions and actions, and in Section 8, I describe some properties of the "executive brain" in orchestrating the complexity of what we observe as human behavior. I consider the risk management implications of the neurosciences perspective in Section 9 and argue that one of the most important aspects of government and regulation is to protect ourselves from our own behavioral patterns by moderating the extremes of fear and greed. I conclude in Section 10 with some thoughts on the potential role that the cognitive neurosciences can play in financial economics.

2 A Brief History of the Brain

It seems obvious that a better understanding of the brain should lead to a better understanding of economic decision-making. Our own subjective experience as human beings strongly suggests that we don't always act rationally or in our own self-interest. Under the influence of strong emotion or stress, or even for no reason we can consciously pinpoint, we've all made decisions that we later regret. In the twenty-first century, we now know that thought takes place in the brain, through the interconnections of nerves, mediated by chemicals and electricity, even if we're unsure of the exact details. It seems eminently logical then that a better understanding of the brain would necessarily lead to a better understanding of how humans make economic decisions.

However, this understanding of the brain is a very new development in science. For decades, if not centuries, the study of economics has been more highly advanced than the study of the brain. Adam Smith sought to explain human behavior in terms of our inner psychology, yet there was no way he could measure the moral sentiments he so eloquently described. As late as 1871, the British economist William Stanley Jevons could write[1]:

Far be it from me to say that we ever shall have the means of measuring directly the feelings of the human heart. A unit of pleasure or of pain is difficult even to conceive; but it is the amount of these feelings which is continually prompting us to buying and selling, borrowing and lending, labouring and resting, producing and consuming; and it is from the quantitative effects of the feelings that we must estimate their comparative amounts.

Modern economics emerged under the assumption that the internal processes leading to an economic decision could *never* be directly measured. This assumption led to the ideas of revealed preference and utility theory, which still form the bedrock of modern microeconomics today.

At the same time that neuroscience was developing a more detailed understanding of how the brain works (see Appendix A), economic theory was becoming more narrowly focused on models of perfectly rational behavior, so much so that despite the intellectual merits of alternatives such as Herbert Simon's "satisficing" theory of bounded rationality, the more mathematically sophisticated rational expectations school of thought pioneered by John Muth (1961) and Robert Lucas (1972) quickly became the dominant perspective of

[1] Jevons, 1871

the economics profession in the 1960s and 1970s. The more empirical, foundational approach of neuroscience had little appeal in that climate, and despite the subsequent explosion of results in the brain sciences, the two fields would have little to say to each other until the 1990s.

3 Fear

All of us who have a stake in tradable markets know that fear is one motivation of our trading behavior. Most of us know to recognize as fear the heart-stopping sensation of watching one bid after another being hit (if we are long) or offers lifted if we are short. It's physically indistinguishable from, say, a prolonged air pocket while flying. The COVID-19 fears in the financial markets are manifold; they range from the fear of losses elicited by price action to fear of the unknown (mainly the duration of the paralysis in economic activity), and passing through the uncertainty about the size and targeting of the government's rescue package.

Appendix B offers a number of examples and insights about the neuroscience of fear.

Fear is the hardwired fire alarm of the brain, setting off sprinkler systems and calling the fire department automatically, sometimes even faster than we know. In his book, *The Gift of Fear*, public safety expert Gavin de Becker points out that we can detect and process subtle cues of impending danger far faster than our conscious minds realize. For example, when the hairs on the back of your neck stand up, that's your fear instinct kicking in, and you should pay attention to it. The amygdala has direct connections to the brainstem, the central switchboard for all the muscles in our body, and this neural shortcut from fear to physical movement is what allows us to (sometimes) duck a punch before we're even aware that someone is trying to hit us. Naturally, these automatic behaviors are extremely useful for survival, particularly in the face of physical threats.

But when taken out of its proper context, our fear circuitry can be counterproductive. To illustrate, I resort to a personal story from my trader days. Although I was not a good manager, I was a good teacher; the most important heuristic I offered my traders was "*lean forward !*". This was a skiing analogy: skiers require training designed to overcome our natural instincts as human beings. For example, an all-too-common mistake among inexperienced skiers is the tendency to pull back to prevent a fall. Pulling back causes the skis to point upwards, and in the face of a threatening situation, it's no surprise that our instinctive reaction is to direct the skis toward the sky and away from the ground. Unfortunately, in this context, our instinct is exactly wrong – pulling back shifts our center of gravity in the wrong direction, making a fall all but certain. The correct but counterintuitive behavior is to lean forward, pointing our upper body towards the ground – which has the effect of restoring our balance. At the desk, "*lean forward !*" meant "let your ego be bruised and take the loss, it can save your career".

The same logic applies to financial investments, where fear can play a productive role if properly balanced against other considerations. The fear of losing money will rationally cause investors to manage their risks actively and in proportion to their expected reward; extreme fear, however, can cause investors to quickly sell all their risky assets at fire-sale prices in favor of government bonds and cash, which may not serve their longer-term objectives if they maintain these holdings for too long. On a broader scale, if we allow our fear instincts to drive our reaction to financial crises, we may eventually regret the policy responses produced by our amygdalas. The work of Kapp, LeDoux, and many others showed that the pathway for fear response in the brain sidesteps the higher brain functions, including the ones we usually associate with rationality. This pathway leads instead to a specific center that processes the *emotional* significance of stimuli. We fear things for reasons outside our conscious, rational mind, and we do this because we have no choice; we are physiologically hardwired to do so. More broadly, we behave, think, reach conclusions, and make decisions with the effects of the emotional brain always running in the background. This has clear implications for economic behavior, as we have seen during the bull market of the past several years, and during the current crisis.

4 Risk

If our reactions to monetary gain are hardwired, what about our reactions to monetary risk? All of us with a stake in financial markets know about risk aversion: it is the behavioral bias that, with very few exceptions, we expect from all others trading in our same market.

In fact, aversion to risk seems nearly universal among all living organisms, most likely a close corollary of the survival instinct. In fact, in a simple evolutionary model of behavior, Thomas Brennan and Andrew Lo have shown that when there are systematic environmental risks to fertility, the forces of natural selection will favor those individuals that are risk averse[2]. The reason is simple: if one course of action leads to three offspring with certainty, and a second course of action leads to a 50/50 gamble of two or four offspring, it can be shown that the first course of action leads to much faster population growth[3]. As we know, the same model of behavior applies to financial markets participants, either consciously (avoidance of negative-NPV investments) or unconsciously (cutting losses to preserve capital). The neuroscience of risk aversion is more fully developed in Appendix C.

But human responses to risk are more subtle than simple risk aversion suggestions. One striking example is the "Peltzman effect", named after the University of Chicago economist Sam Peltzman who, in 1975, published a controversial study showing that government regulations requiring the use of automobile safety devices such as seat belts did little to reduce the number of highway

[2]Brennan and Lo, 2011

[3]This is a consequence of Jensen's Inequality, which, in this simple example, is illustrated by the fact that the safe choice yields 3 x 3 =9 individuals after two generations whereas the risky choice yields 2 x 4 =8 on average. See Brennan and Lo (2011) for a more formal derivation.

deaths because people adjusted their behavior accordingly, presumably driving faster and more recklessly[4]. In fact, some of his data showed that over time, while the number of fatalities among auto occupants did decline, this benefit was almost entirely offset by an *increase* in the number of pedestrian deaths and nonfatal accidents. He concluded that the benefits of safety regulations were mostly negated by changes in driver behavior.[5] Thus, the Peltzman effect explains why the low volatility made possible by the post Great Recession monetary policy led to a sustained bull market, a yield-chasing feeding frenzy in corporate credit, and the development of certain-to-die products, such as short-vol ETFs and funds. The unconventional monetary policy provided the safety net which caused us to dare to "drive faster".[6] When the only goal is to reduce driving time, it seems perfectly rational that increased safety would induce drivers to drive faster. From a financial perspective, this is completely consistent with basic portfolio theory: if an asset's volatility declines but its expected return remains unchanged, investors will put more money into such an asset, all other things (correlations to other assets, etc.) being equal.

But what if safety improvements are *perceived* to be more effective than they are? Then drivers may end up taking more risk than they intended to, simply because they felt safer than they really were. Risk perception may differ from risk reality, and this is obviously a critical factor in COVID-19 crisis. Given the extraordinarily low volatility in the prices of financial assets which ensued from sustained heterodox monetary policies, certain investors may have thought they were safer than, in fact, they were. This adaptive nature of human risk preferences is one of the most important reasons for producing accurate and timely risk analytics in financial contexts. What's more, those analytics need to be grounded in real science; i.e. statistics and data science need to be backed by the sound use of probability theory.

5 Rationality

Overrides of the rational process lead to bad outcomes for investors, especially in times of crisis and, as shown in Appendix D, emotion is not the only possible source of irrationality.

What, then, is the source of irrationality, if not emotion? The neuroscience

[4]Peltzman, 1975

[5]Since then, many studies have extended Peltzman's original study by considering additional safety devices such as airbags, anti-lock brakes, crumple zones, etc. In some cases these new studies have confirmed, and in other cases they've refuted Peltzman's findings after controlling for other confounding factors such as enforcement practices, driver age, rural vs. urban roads, vehicle weight, and so on[5a] [redacted] See, for example, Crandall and Graham (1984), Farmer el al. (1997), and Cohen and Einav (2003). These ambiguous results are not surprising given the many different contexts in which we drive automobiles. While it seems reasonable that a harried commuter would certainly take advantage of improved safety by driving faster and getting to work a few minutes earlier, the same probably doesn't hold for vacationers touring the countryside.

[6]However, in the most recent study of this genre, two economists, Russell Sobel and Todd Nesbit, decided to turn their attention to the one driving venue where there are very few

perspective provides a hint, from which we can craft a conjecture. Neuroscientists have shown that emotion – especially fear and the fight-or-flight response – is the "first response" in the sense that we exhibit emotional reactions to objects and events far more quickly than we can articulate what those objects and events are[7]. In fact, extreme emotional reactions can "short-circuit" rational deliberation altogether (see Baumeister, Heatherton, and Tice, 1994), i.e., strong stimulus to the amygdala seems to inhibit activity in the prefrontal cortex, the region of the brain associated with logical deliberation and reasoning ability. From an evolutionary standpoint, this seems quite sensible – emotional reactions are a call-to-arms that should be heeded immediately because survival may depend on it, and higher brain functions such as language and logical reasoning are suppressed until the threat is over, i.e., until the emotional reaction subsides.

However, while the "threats" identified by the amygdala in a market environment are not, in fact, life-threatening, our physiological reactions may still be the same. In such cases, the suppression of our prefrontal cortex may be unnecessary and possibly counterproductive, which is implicit in the common advice to refrain from making any significant decisions after experiencing the death of a loved one, or a similar emotional trauma. This is sage advice, for the ability to "think straight" is genuinely physiologically hampered by extreme emotional reactions[8]. Therein lies our current challenge: in times of panic we need to consciously engage our prefrontal cortex and not let the amygdala be the sole decision-maker.

What we consider to be "rational" behavior is, in fact, a complex balancing act between a number of components of the brain, some hardwired, others more adaptive, and if these components become imbalanced – either too much fear or too little greed – we observe "maladaptive" behavior. Therefore, the definition of rationality, and its opposite, is inextricably tied to an individual's environment. The great white shark moves through the water with fearsome grace and efficiency, thanks to 400 million years of natural selection – but take that shark out of water and onto a sandy beach, and its flailing undulations will seem quite irrational. The origins of human behavior are similar, differing only in the length of time we have had to adapt to our environment (about 2 million years), and the speed with which that environment is now changing, thanks to technological advances. Evolutionarily advantageous responses by *homo sapiens* to threats on the plains of the African savannah 50,000 years ago may not be as effective in dealing with threats on the trading floor.

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confounding factors, and there's no doubt that all drivers are intensely focused on getting to their final destination as quickly as possible – NASCAR races[6a][redacted]Sobel and Nesbit, 2007.. Their conclusion: "Our results clearly support the existence of offsetting behavior in NASCAR – drivers do drive more recklessly in response to the increased safety of their automobiles" .

[7]See Section 3, de Becker (1997), and Zajonc (1980, 1984).

[8]Other familiar manifestations of the antagonistic effect of emotion on the prefrontal cortex include being so angry that you cannot see ("blinded by your anger", both physically and metaphorically, and becoming tongue-tied and disoriented in the presence of someone you find unusually attractive. Both vision and speech are mediated by the prefrontal cortex.

6 Sentience

While neuroscience clearly shows that the human decision-making process is very far from the hyper-rationality of *homo economicus*, the efficient markets hypothesis suggests that this might not matter very much. Consider a modern financial market with many traders. If one trader makes a poor decision under the heat of emotion, another trader acting more rationally should see this as an arbitrage opportunity and make an easy profit. Of course, we know that this ideal depiction of the wisdom of crowds does not always happen – entire markets can be infected with what the nineteenth-century journalist Charles Mackay called "the madness of crowds" – but it does happen far more often than not. But what if there were biological limits to human rationality itself?

It's a truism in freshman economics that price is determined by supply and demand, but each economic transaction has a buyer and a seller, each trying to come to a mutually satisfying agreement via Jevons's aforementioned "double coincidence of wants". If a seller refuses to lower the asking price to a level a buyer wishes to bid, no transaction will take place. That might be a rational decision on the seller's part. On the other hand, it might reflect a lack of awareness of what the buyer is willing to offer. A well-functioning market's price-discovery process requires participants to engage in a certain degree of cause-and-effect reasoning: "If I do this, then others will do that, which means I should . . . " This chain of logic presumes that individuals have what psychologists call a "theory of mind" – the ability to understand another person's mental state. To understand why, consider the most basic form of bilateral negotiation between a buyer and a seller; even the simplest back-and-forth process of price discovery requires that the buyer understand the motives of the seller, and vice versa. In fact, to compute the equilibrium price – as hypothesized by rational expectations and efficient markets theory requires an unending recursive chain of reasoning, as if buyer and seller were trapped in a hall of mirrors: the seller knows that the buyer knows that the seller knows that the buyer knows that the bid is too high, etc. In other words market equilibrium requires a rather *sophisticated* theory of mind, and presumably a high level of abstract thought.

How far does this hall of mirrors extend? While Appendix D contains the neuroscientific answer, we might suspect, on purely theoretical grounds, that the potential for infinite regress is present in humans, even if rarely used. After all, the English language can support infinite levels of clauses in its grammar, as in the nursery rhyme "This is the cat that killed the rat that ate the malt that lay in the house that Jack built", and so on. On the other hand, we might try to construct a mental experiment about a third-order false belief – George thinks that Elizabeth thinks that David thinks etc. – and come to the conclusion that it's rather difficult. In fact, psychological tests have shown that normal adults start making significant errors when answering questions about the fifth-order theory of mind[9]. This has implications for the assumption of human rationality in the efficient markets hypothesis. It is not very difficult to construct

[9] Kinderman, Dunbar, and Bentali, 1998.

a scenario where correct knowledge regarding another individual's intentions five layers removed from a given transaction has economic implications, whether in a complicated restructuring deal or in the terms of an exotic financial derivative. But if it's impossible for all but a very few chess grandmasters to hold such a chain of intentions as a single thought – impossible in the same way that a young child literally cannot understand that his parent does not know where his blanket is – how can an investor always act rationally to maximize his or her profit? Alternatively, if the investor fails to act rationally, how can other investors know they are taking successful advantage of the failure? This might involve a sixth-order theory of mind. While the arbitrage mechanism can correct misjudgments, it relies on the ability of investors in the market to recognize when a correct judgment by the market has taken place. In some cases, this expectation is simply unrealistic.

7 Interactions

While we are able to describe the interactions between parts of an investor's brain in times of crisis, neuroscience's advances in this field lag behind others. Therefore, our insights on this matter are of a "voluntarist" nature, essentially "Do not let your amygdala interfere with the use of your prefrontal cortex". Easier said than done.

Although neuroscience has had many breakthroughs in the last few decades, one of the most important questions about human cognition has yet to be answered: how do the individual components of the brain interact to produce observed human behavior? We now know a great deal more about how fear and greed are physiologically generated, but what can we say about how an investor will respond to a 20% decline in his portfolio? Despite the fact that the fight-or-flight response may be triggered by such an event, not all individuals will react in the same manner – some may panic and switch their portfolio to cash immediately; others may not react at all. Can neuroscience provide any insight into these individual differences and the underlying mechanisms by which such heterogeneity arises? From the economist's point of view, these kinds of questions are the most relevant; they are also the most difficult to answer from the neuroscientific perspective.

While we don't yet have a complete theory of how the brain works, there are a few observations that hint at how the various components of the brain interact.

The first observation is that not all neural components are created equal. From an evolutionary perspective, certain components are much older than others and are found in many species in addition to *homo sapiens*. Therefore, these common components are more likely to engage in functions that are critical for basic survival across all species. For example, pain receptors exist in virtually all mammals and reptiles; hence pain avoidance and fear conditioning is equally ubiquitous and obviously critical for survival. This universality implies a certain priority in its impact on behavior: pain avoidance and fear trump all other neural components under sufficiently threatening circumstances, as they should. While a 20% decline in one's portfolio might not lead to the same response across a diverse population of investors, a raging fire in a crowded theater will.

The prefrontal cortex is a remarkable piece of neural machinery that, in the blink of an eye on an evolutionary time scale, has allowed humans to dominate their world and spread to virtually every type of environment on this planet and its moon. The prefrontal cortex is the closest thing to rational expectations and *homo economicus* that the brain has to offer to economists. If agents maximize expected utility subject to budget constraints, or optimize portfolios via quadratic program- ming, or engage in strategic subterfuge in a dynamic bargaining context, they will be using the prefrontal cortex to do so.

But like any organ of any living being, there are limits to its capabilities.

The examples in Appendix E highlight the complexity and subtlety of *homo sapiens*, but they also offer hope that we can one day develop a more complete understanding of human behavior that integrates economics, psychology, and neuroscience in mutually beneficial ways[10].

8 Implications for Investors

Although the perspective outlined in this article has been largely qualitative, nevertheless it does offer several practical implications for investors. One immediate implication is that individual behavior is a complicated and dynamic medley of several decision-making neural components, including primitive hardwired responses such as fight-or-flight and more refined processes such as logical deliberation and strategic planning. Assuming that individuals or populations always behave in only one manner or the other is too simplistic and may lead to ineffective or counterproductive investment decisions. Financial markets and their participants are rarely always rational, nor are they always emotional. Instead, they engage in both types of mental processes and are constantly adapting and evolving to new sets of circumstances. Under this "Adaptive Markets Hypothesis", many of the tenets of market efficiency and rational expectations may not hold at all times, but they do serve as useful benchmarks that reality may eventually approximate under certain conditions[11]. In particular, if environmental conditions are relatively stable, then the process of natural selection will eventually allow market participants to successfully adapt to such conditions, after which the market will appear to be quite efficient. However, if the environment is unstable, as it is now, then market dynamics will be considerably less predictable as some "species" lose their competitive edge to others, and the market may appear to be quite inefficient. Indeed, the evolutionary theory of "punctuated equilibrium" – in which infrequent but large environmental shocks cause massive extinctions followed by a burst of new species – may be just as relevant to economic contexts.

If punctuated equilibria also characterize financial markets, then strategies designed under the assumptions of rationality will be inappropriate during pe-

[10] Lo, 2010. [11] Lo (1999, 2004, 2005)

riods of financial distress, and policies designed to deal with periods of distress will be inappropriate during periods of calm. The adaptive markets hypothesis suggests that the most effective trading strategy is one that adapts to changing environments and populations. Countercyclical leverage is one example, but there are many other possibilities for revamping existing strategies to be more responsive to current systemic exposures.

Another implication of the neuroscience perspective is that there is a biologically mandated hierarchy of the components of the brain that should be respected. Fear, particularly fear of the unknown, overrides most other decision-making components, and once triggered, this circuit can be very difficult to interrupt. Investors should strive to accumulate information to bound the unknown within limits. In the COVID-19 situation the biggest fear is, obviously, the severity and longevity of output contraction. To the extent that governments and companies around the world publish reliable information, we can bound our fears by, at least, a worst-case scenario. Only through such gathering of trusted information can we successfully manage and, ultimately, eliminate fear. FDR was more right than he knew when he said, "The only thing to fear is fear itself", but he should have added that fear is, indeed, a fearsome force of nature that should be greatly feared and actively managed.

If the active management of fear involves greater gathering and analysis of trusted data, a prerequisite is the collection of information regarding systemic risk – it is a truism that one cannot manage what one does not measure. Therefore, the starting point for any serious discussion of systemic risk management must be the raw data on which risk measures are based. In my opinion, some of such data is currently deficient (e.g., we don't know corporate daily cash balances) and remains a source of fear.

The importance of measurement goes hand-in-hand with the executive function of delayed gratification and pain avoidance. An individual or institution can be expected to voluntarily reduce or discontinue an otherwise currently pleasurable or profitable activity under only two conditions: the change may result in even greater pleasure or profit later, or the change may reduce the likelihood of pain in the future. Absent both of these conditions, the neural incentives to reduce risk are also absent; hence the importance of gathering reliable data to provide investors with the appropriate information on which they can weigh the fear of future losses against the pleasure of current gains. As Damasio's elegant explication of rationality shows, only through the proper balance of fear, greed, and other emotional debits and credits can we make good decisions.

9 Conclusion

One of the most significant consequences of the Financial Crisis of 2007–2009 was the realization that the intellectual framework of economics and finance was incomplete in several respects. Unfortunately, that remains the case. While the 2007-2009 Financial Crisis has exposed some of the limitations of neoclassical economics, critiques of traditional economic theory have been accumulating from within the profession for quite some time. The conflict between the rational expectations paradigm of economics and the many behavioral biases documented by psychologists, behavioral economists, sociologists, and neuroscientists has been hotly debated for decades. Rational expectations and its close cousin, the efficient markets hypothesis, have come under fire recently because of their apparent failure in predicting and explaining the Great Recesion.

But it is easy to forget the many genuine breakthroughs that have occurred in economics since the Great Recession and which better equip us to deal with the current financial panic. Those advances involved areas as diverse as general equilibrium theory, game theory, growth theory, econometrics, portfolio theory, and option-pricing models. To be sure, there are legitimate arguments that the rigorous and internally consistent economic models of rational self-interest – models used implicitly and explicitly by investors to set strategy, manage leverage, and rein in risk-taking – are deficient. Even the most sophisticated stochastic dynamic general equilibrium models did not account for a pandemic with a relatively modest mortality rate ravaging the world economy. In my opinion, this is the failure of models built by data scientists who do not know enough about probability theory.

Rather than discarding rationality altogether, a more productive response may be to confront the inconsistencies between economic models of behavior and those from other disciplines – and attempt to reconcile them and improve our models in the process. While frustrating, contradictions often present opportunities for developing a deeper understanding of the phenomena in question. In particular, neuroscience, psychology, anthropology, sociology, and economics all intersect with respect to human behavior, and when these disparate fields share the same object of study, their respective theories must be mutually consistent in their implications.

For example, neurophysiological mechanisms of risk processing must be consistent with psychological experiments involving human subjects choosing among risky alternatives; otherwise, flaws exist in one or both of these bodies of knowledge. By reconciling the inconsistencies and contradictions between disciplines, we can develop a broader and deeper understanding of *homo sapiens.*

This approach highlights the value of "consilience" , a term reintroduced into the popular lexicon by the great evolutionary biologist E.O. Wilson (1998), who attributes its first use to William Whewell's 1840 treatise *The Philosophy of the Inductive Sciences*, in which Whewell wrote: "The Consilience of Inductions takes place when an Induction, obtained from one class of facts, coincides with an Induction, obtained from another different class. This Consilience is a test of the truth of the Theory in which it occurs". In this article, I hope to have facilitated the consilience between financial economics and the neurosciences.

Appendices

A The Neuroscience of the Brain

The scientific study of the brain would remain backwards for quite some time. During Jevons's time, even the idea that nerves were composed of independent cells was still in doubt. This is surprising to us today, when children's books and prescription drug commercials routinely contain illustrations of neurons, admittedly sometimes fanciful, and how they work. It took the laboratory advances of the Italian pathologist Camillo Golgi and the close observations of the Spanish pathologist Santiago Ramon y Cajal to demonstrate the validity of the "neuron theory" , using state-of-the-art microscopic techniques for their time. Golgi and Ramon y Cajal were quickly honored for their work, jointly winning the Nobel Prize in Physiology or Medicine in 1906 (although Golgi himself was not a believer in neuron theory).

In the same way, most scientists were skeptical that the brain contained specialized regions for different purposes until remarkably late in the scientific era. Today, we refer casually to "speech centers" or "visual centers", and it is natural for us to speculate if there is a particular part of the brain which assesses economic value or financial risk, but for much of the modern era, this would have sounded like nonsense to an educated person. This can be explained in part by the sociology of science. In the mid-eighteenth century, the Swedish philosopher Emanuel Swedenborg correctly described the specialized nature of the cerebral cortex, linking its structures of nerve fibers to their function, but Swedenborg was also known for his religious writings about dreams and angels (there is still a Swedenborg Chapel on the Harvard campus), and his hypothesis was ignored for decades[12]. Meanwhile, the physiologist Franz Joseph Gall also believed that different parts of the brain had different functions; however, he believed that these were reflected in the external shape of the skull. This led to the pseudoscience of phrenology, through which one's personality could be determined by examining the bumps on one's head, a theory which was quite popular in the first half of the nineteenth century. Eventually, this discipline came into disrepute, creating a certain degree of skepticism-by-association for the heterogeneous nature of the brain.

This skepticism was slowly overturned in the nineteenth century, principally through the study of individuals with brain tumors, lesions, or other head injuries. One of the most celebrated cases was of a young New Hampshire man named Phineas Gage, who had an iron rod pass under his upper jaw and through the top of his head during a rock-blasting accident in the construction of the Rutland & Burlington Railroad in 1848. Gage survived and recovered from this horrific accident – well enough to later become a stagecoach driver in Chile – but his personality and habits changed markedly. Gage's case is especially interesting from an economic point of view. In the words of his doctor, writ-

[12]Finger, 1994.

ing several years after Gage's death, "The equilibrium or balance, so to speak, between his intellectual faculties and animal propensities, seems to have been destroyed". Before the accident, Gage was "a shrewd, smart businessman, very energetic and persistent in executing all his plans of operation". After the accident, however, Gage was "impatient of restraint or advice when it conflicts with his desires, at times pertinaciously obstinate, yet capricious and vacillating, devising many plans of future operations, which are no sooner arranged than they are abandoned in turn for others appearing more feasible"[13]. It was as though an important component of Gage's ability to plan ahead *rationally* had been removed along with part of his brain.

As interesting as these hints to the brain's function were to medical researchers, they made very little impact on the field of economics. Even Keynes, with his interest in medical psychology and psychiatry, could only invoke "animal spirits" as a characteristic of human nature in 1936: "a spontaneous urge to action rather than inaction, and not as the outcome of a weighted average of quantitative benefits multiplied by quantitative probabilities"[14]. While Keynes's animal spirits are an evocative metaphor against the concept of *homo economicus* – rational economic man – they sound far too shaman-like to be very satisfying as an explanation for human behavior today[15].

[13]Harlow, 1868. [14]Keynes, 1936.

[15]Keynes himself took the term from the Scottish Enlightment philosopher David Humes' *Enquiry Concerning Human Understanding.*

B The Neuroscience of Fear

B.A Norton

Several years ago, Robert Thompson, an airline pilot, stopped at a convenience store to pick up a few magazines, but he turned around and walked right out of the store that he just entered because he felt afraid, even though at the time he couldn't understand why[16].It turned out the store was being robbed at gunpoint, and shortly after Thompson left, a police officer entered the store and was shot and killed. Only afterwards – with some thoughtful debriefing by Gavin de Becker, a public safety expert – did Thompson realize some of the things that may have triggered his discomfort: a customer wearing a heavy jacket despite the hot weather, the clerk's intense focus on that customer, and a single car with the engine running in the parking lot. But Thompson's decision to leave the store came almost instantaneously, long before he was even aware that he had observed anything unusual.

B.B The Amygdala

Fear of the unknown – FDR's "nameless, unreasoning, unjustified terror" – is one of the most powerful motivating forces of our conscious and subconscious minds. Neuroscientists have demonstrated with remarkable detail that our fear circuitry is highly refined, in some cases reacting much faster than we can perceive. The "fight or flight" response, hardwired in all mammals, is just one example of the wonderful evolutionary mechanisms that have kept our species alive for the past 100,000 years. But physical threats are not the same as financial threats, and while high blood pressure, dilated blood vessels in our muscles, and a rush of adrenaline may protect us from the former, they do little to shield us from the latter. In fact, sustained emotional stress has been shown to impair rational decision-making abilities, leading to some well-known behavioral biases such as "doubling down" rather than cutting losses, selling at the bottom and buying back at the top, and other financial traps that have confounded most retail investors and not a few professional traders.

To develop a deeper understanding of how fear works, we have to look inside the human brain, perhaps the most complicated structure known to science. Most estimates put the number of neurons in the brain at around one hundred billion, not counting the many other important cell types found there[17]. Each neuron can have several thousand synapses sending signals to other cells, forming an incredibly dense network of interconnections between neurons. In comparison, the number of human beings that have ever lived is estimated to be substantially less than one hundred billion. If the average person throughout history only made a few hundred personal connections in his or her lifetime (as seems likely), the extended social network of everyone who has ever lived is still

[16] de Becker, 1997.

[17] See Williams and Herrup (1988). Of course this is only an "order of magnitude" estimate: the total number has never been physically counted

much less complex than a single human brain.

The brain is not only complicated, but also extremely difficult to examine while functioning. It is, in effect, what the mathematician Norbert Wiener called a "black box" , by which he meant not an airplane's flight-data recorder (those are brightly colored orange, incidentally), but an opaque system where one can only examine the inputs and the outputs. For many years, information on how the black box functioned internally was scarce. Brain researchers could only rely on evidence from post-mortem neuroanatomy, case studies after brain surgery or other head injuries like Phineas Gage, and rather distressing "ablation" experiments – in which regions of the brain are selectively destroyed surgically to see what the impact is – performed on rats, monkeys, and other creatures, under the assumption that brain functions are similar in evolutionarily related species.

One such experiment took place in 1937, the year after Keynes made his pronouncement about "animal spirits" . Two researchers, the German emigre psychologist Heinrich Kluver and the American neurosurgeon Paul Bucy, were attempting to discover which areas of the brain were involved in the visual hallucinations caused by mescaline, the active chemical compound in peyote cactus. In one set of experiments, Bucy removed the temporal lobes of the lateral cerebral cortex of rhesus monkeys (in humans, this part of the brain is slightly above and behind the ears). Kluver and Bucy discovered something startling: the monkeys' ability to see was not impaired, but their ability to recognize objects was. "The hungry animal, if confronted with a variety of objects, will, for example, indiscriminately pick up a comb, a Bakelite knob, a sunflower seed, a screw, a stick, a piece of apple, a live snake, a piece of banana, and a live rat. Each object is transferred to the mouth and then discarded if not edible". At the same time, the monkeys also lost their sense of fear, behaving calmly in the presence of humans and snakes. Kluver and Bucy called this behavior "psychic blindness"[18]. The monkeys apparently suffered no loss of visual acuity, but what they saw had lost the set of emotional and physical associations they previously conveyed.

This was a remarkable result – a particular part of the brain was responsible for mediating the emotional response to recognizing an object. We live in a world where image recognition by computers is becoming more common by the day, and we tend to think of it as an unemotional, purely rational act. It would be disconcerting, to say the least, if we discovered that the software processing photographs of license plate numbers in speed traps had emotion-like responses based on the numbers it recognized – but that's exactly what occurs in the brain.In fact, the brain appears to have several pathways that mediate emotion. Kluver and Bucy had fortuitously removed the part of the brain essential for linking memories to fear: the amygdala.

The amygdala is a small but distinct structure located deep within the brain. In humans, it is located roughly where a line entering one's eye and a line

[18]Kluver and Bucy (1937). Kluver-Bucy syndrome was later found in humans, although it is very rare

entering one's ear would intersect. Like most brain structures, the amygdala is paired. Early anatomists thought it resembled an almond, hence its name, *amygdala* (the Latinized form of the Greek word for "almond"). Researchers following in Kluver and Bucy's footsteps suspected that it was involved in how the brain learned fear. It was not until the late 1970s, however, when the first neurophysiological studies used the technique of fear conditioning to examine the function of the amygdala.

Even though it's over a century old, everyone knows the story of Pavlov and his dogs: the Russian scientist would ring a bell while feeding his dogs, and the dogs became so conditioned to the sound of the bell that they would still salivate when Pavlov rang his bell, even if they weren't fed. Fear conditioning involves replacing the unconditioned stimulus – in Pavlov's experiments, food – with a negative stimulus such as an electric shock. Conditioned fear learning is much faster than other forms of learning. It can take place even in a single session of linked stimuli, and compared to other forms of learning, it is nearly indelible. There are sound evolutionary reasons for this asymmetry, and the same kind of fear conditioning has been found throughout the animal kingdom, not merely in mammals.

In 1979, Bruce Kapp and his team at the University of Vermont first published evidence that lesions on the central nucleus of the amygdala disrupted fear conditioning in rabbits[19]. Inspired by this work, Joseph LeDoux (then at Cornell University Medical College in New York City; now at New York University's Center for Neural Science), set out to trace exactly how a fear-conditioned stimulus was processed by the brain. In his book, *The Emotional Brain*, LeDoux recounts how he discovered that pathway, or as he puts it, "the road map of fear"[20]. LeDoux made lesions in the brains of rats conditioned to fear a specific sound, working backwards along the known pathways for auditory processing. LeDoux writes, "My approach was to let the natural flow of information be my guide . . . I reasoned that damaging the ear would be uninteresting, since a deaf animal is obviously not going to be able to learn anything about a sound. So, instead, I started by damaging the highest parts of the auditory pathway". It turned out that damaging the higher auditory functions in the cortex – the 'rind' of the brain – had no effect on fear conditioning. Damaging the auditory thalamus further in did. This posed a puzzle for LeDoux: where did the road map of fear lead, if not along the standard auditory pathway? To find the answer, LeDoux injected a special chemical tracer into the auditory thalamus. The neurons there absorbed the tracer and sent the chemical down the long thin connections of the axons to the next stage of the pathway. The brains were then sectioned and stained to determine where the tracer ended up: "Bright orange particles formed streams and speckles against a dark-blue background. It was like looking into a strange world of inner space". LeDoux found four regions that contained the tracer. Three of those regions, when damaged, showed no change in response in fear conditioning. The fourth region was the amygdala. The amygdala, it turned out, was the final destination of the road map of fear.

[19]Kapp, 1979. [20]LeDoux, 1996.

B.C Dopamine

In 1954, two researchers at Montreal's McGill University, James Olds and Peter Milner, implanted electrodes into the septal area of the brains of rats. These rats were placed in Skinner boxes with a lever which, when pressed, would deliver a low voltage of 60-cycle alternating current to the rat's brain. These rats then did something remarkable: they would *choose* to have their brains electrically stimulated by repeatedly pressing the lever – on one occasion, almost two thousand times an hour! Olds and Milner were careful to rule out that the voltage was reducing the pain of implantation instead (understandably so)[21].

This strongly suggested to neuroscientists that there was a "pleasure center" in the brain. In fact, many electrode studies were performed across a variety of animals to find the pleasure center, including several (of dubious ethics) on humans. As with most things involving the brain, however, it was more complicated than it first appeared. Instead of a pleasure center, the brain seems to have a reward system. The term "reward" may be a little confusing to the reader with an economics background; in psychology, a "reward" is anything positive which makes a behavior more likely. Rewards can be as basic and fundamental as food, or as abstract and intangible as intellectual satisfaction. Surprisingly, all these different rewards food, sex, love, money, music, beauty – appear to use the same neurological system. Moreover, the pathways of this system all transmit the same chemical signal: dopamine.

Dopamine is a comparatively simple compound that was once thought to have very little neurological significance. It was best known as a precursor to adrenaline in the body until in 1957 the Swedish researcher Arvid Carlsson showed that it was in fact a neurotransmitter, a discovery for which he won the Nobel Prize for Physiology or Medicine in 2000[22]. Carlsson had given reserpine, a drug known to deplete neurotransmitters, to rabbits, which then fell into a catatonic state. Carlsson theorized that the rabbits' catatonia was caused by a lack of an as-yet-undiscovered neurotransmitter. By injecting the rabbits with L-DOPA, a chemical which would be converted to dopamine in the brain, Carlsson was able to revive the rabbits leading the Greek-American neurologist George Cotzias only a few years later to successfully treat patients with Parkinson's disease, and the neurologist Oliver Sacks to treat paralyzed patients with sleeping sickness, as celebrated in his famous book *Awakenings*[23].

One peculiarity of patients treated with L-DOPA was that they often became addicted to gambling. This was one of the first clues that dopamine was involved in the brain's reward system. Other researchers discovered that addictive drugs such as cocaine and methamphetamine flooded the brain with dopamine through the mesolimbic pathway, releasing it into the nucleus accumbens, which is located not very far from the septal area where Olds and Milner had implanted their electrodes. Neuroanatomists have now discovered eight separate dopamine pathways in the brain, including ones associated with attention and learning. While the full picture of how dopamine and the reward system interact is still far from clear, there is growing consensus among neuroscientists

[21] Olds and Milner (1954) [22] Carlsson et al., 1957. [23] Sacks, 1974.

that the broad outlines have been established[24].The implications for financial crisis is clear: an imbalance in an individual's dopamine system can easily lead to greater risk-taking, and if risk-taking activities are, on average, associated with financial gain, a potentially destructive positive-feedback loop can easily emerge from a period of lucky draws.

B.D The Brain's Reward System

In another fascinating study of the brain's reward system, a team led by Hans Breiter at Harvard Medical School and Massachusetts General Hospital, and including the participation of psychologist Daniel Kahneman, used a technique known as "functional magnetic resonance imaging" (fMRI) to determine which areas of the brain were activated when an individual experienced monetary gains and losses[25]. This experimental design involves placing a subject in an MRI machine (a long horizontal tube surrounded by a powerful magnet), attaching a mirror at a 45-degree angle to the ceiling of the tube (so the subject can see a computer screen placed just outside the tube), asking the subject to engage in a variety of computer- generated tasks requiring only simple mouse-clicks (which subjects can do since their hands are free), and imaging their brains all the while.

What does fMRI actually measure? This is an important question in all imaging studies, and indeed in all physiological studies of the human brain. The common denominator for all such studies is to find physical "correlates" to internal mental processes within the black box of the brain – minute physiological changes that correlate to subjective experience. In the most commonly used form of fMRI – blood-oxygenation-level-dependent contrast fMRI (BOLD fMRI) – the oxygenation levels of the blood throughout the brain are measurable because hemoglobin molecules without oxygen respond more strongly to a magnetic field than those with oxygen. Neuroscientists reason that in an active region of the brain, the neurons will use more oxygen than average, implying that the level of deoxygenated hemoglobin in that area will increase relative to other areas. In deactivated regions of the brain, in comparison, the neurons will use less oxygen than average. In this way, fMRI data can show which regions of the brain become more active (or less active) in response to a given task.

In Breiter's study, subjects were given a \$ 50 stake (in real money, unlike other fMRI experiments), and while in the fMRI machine, they were asked to play a simple gambling game. On the computer screen that was projected into the tube in which they lay, one of three computer-animated spinners was displayed, similar to the kind found in children's board games. Each spinner was divided equally into three possible outcomes: the 'good' spinner with \$ 10, \$ 2.50, and \$ 0; the 'intermediate' spinner with \$ 2.50, \$ 0, and \$ -1.50; and the

[24]It is tempting to speculate that because of the multiplicity of uses and pathways of dopamine in the brain, we have many ways to feel pleasure, while we have only one way to feel fear. There is some support for this asymmetry from pure evolutionary grounds.

[25]Breiter et al., 2001

'bad' spinner with \$ 0, \$ -1.50, and \$ -6[26].The arrow on the spinner was timed to take six seconds to reach its final destination, long enough for the fMRI to image the "prospect" phase in the subject. Once the spinner stopped, the arrow flashed for six more seconds, long enough for the fMRI to image the "outcome" phase. Unknown to the test subjects, the outcomes of the spinners only appeared to be random. In fact, the spinners went through a preprogrammed sequence such that each subject earned \$ 78.50 by the end of the experiment.

What did Breiter, Kahneman, and their colleagues find? As the monetary rewards increased, so did the activation in: the nucleus accumbens, part of the reward system; the sublenticular extended amygdala, associated with emotional reaction; the hypothalamus, a part of the brain closely linked to the endocrine hormonal system; and the ventral tegmental area, which releases dopamine into the reward system. This was a direct neurological correlate to monetary reward.

Even more intriguing, the pattern of activations in the monetary reward process looked extremely familiar to Breiter. In fact, it was the same pattern he had found a few years before in another study he conducted with cocaine addicts and first-time morphine users. In the human brain, monetary gain stimulates the same reward circuitry as cocaine – in both cases, dopamine is released into the nucleus accumbens, reinforcing the behavior. In the case of cocaine, we call this addiction. In the case of monetary gain, we call this capitalism. In other words, our most fundamental reactions to monetary gain are hardwired into human physiology.

Neuroscientists have also attempted to link the results of fMRI research directly to economic theory. For example, Read Montague at Baylor Medical Center and Gregory Berns at Emory University School of Medicine have tried to discover how the brain's different reactions to financial reward translate into an internal mental "currency". They suspect that the brain uses a common scale of valuation to compare different outcomes. In their view, due to the vast multiplicity of possible human behaviors, the brain needs a single internal scale of representing value to choose a proper course of action – although this course of action might not be rational from the standpoint of *homo economicus*[27].

Other researchers have tried to use fMRI research to *predict* economic behavior. Since many brain regions are activated before a specific type of behavior – e.g., the nucleus accumbens and risk-seeking – Brian Knutson and Peter Bossaerts at Stanford University have theorized these anticipations could be used to create a "physiologically constrained" theory of decision-making[28]. This is somewhat reminiscent of Herbert Simon's attempt to emulate the psychology of the human decision-making process in a computer program. Here, however, the neurological correlates could be directly measured by fMRI and other brain imaging techniques, and the resulting behaviors compared against the results of the theoretical model.

[26]As the experimenters note: "The gains were made larger than the losses to compensate for the well-established tendency of subjects to assign greater weight to a loss than to a gain of equal magnitude", a psychological result which comes directly from Kahneman and Tversky's research.

[27]Montague and Berns, 2002. [28]Knutson and Bossaers, 2007.

Of course, the fMRI method has its limitations. Its spatial resolution, which can detect volumes the size of a grain of sand or the head of a pin, is much too coarse to detect the activity of a single neuron, or even of a small group of neurons. Its resolution in time is even coarser, taking several seconds to build up a single image[29]. Some researchers are skeptical of the chain of logic which links deoxygenated blood to local brain activity; at best, they argue, it is imperfectly correlated. Moreover, even under the most favorable conditions, fMRI only provides the researcher with brain-activity data. It is a little as though someone were attempting to study how New York City worked, but the only information they had about the city was the power company's meter readings block by city block. It would take a truly skilled researcher to discover the purpose of the Financial District or Broadway from that data, and events the Puerto Rico Day parade would effectively be invisible to the researcher.

Nevertheless, fMRI has been revolutionary in allowing researchers to see inside the "black box" of the brain as they never could before. Entirely new areas of research linking neuroscience to economics and finance have emerged thanks to the use of fMRI, and we have barely scratched the surface of potential insights from this tool. In particular, we haven't touched on higher brain functions such as logical reasoning, numerical computation, and long-term planning, all intimately involved in the economic and financial decision-making process. Nor have we faced the thorny questions of intelligence and consciousness, about which we are still in a state of deep ignorance, even if our knowledge is growing exponentially each day.

[29] In comparison, the old-fashioned electroencephalograph could record changes in the brain's surface electrical activity.

C The Neuroscience of Risk-Taking

Even when risk is accurately measured, human behavior shows some very interesting biases in how losses and gains are weighed. For example, consider a slightly modified version of an experiment conducted by Daniel Kahneman and Amos Tversky in 1979 for which Kahneman was awarded the Nobel Prize in Economics in 2002[30]. Suppose you're offered two investment opportunities, A and B: A yields a sure profit of $ 240,000, and B is a lottery ticket yielding $ 1 million with a 25% probability and $ 0 with 75% probability. If you had to choose between $ 250,000 which is higher than A's payoff, you may not care about this fact because you'll receive either $ 1 million or zero, not the expected value. It seems like there's no right or wrong choice here; it's simply a matter of personal preference. Faced with this choice, most subjects prefer A, the sure profit, to B, despite the fact that B offers a significant probability of winning considerably more. This is an example of risk aversion.

Now suppose you're faced with another two choices, C and D: C yields a sure loss of $ 750,000, and D is a lottery ticket yielding $ 0 with 25% probability and a loss of $ 1 million with 75% probability. Which would you prefer? This situation is not as absurd as it might seem at first glance; many financial decisions involve choosing between the lesser of two evils. In this case, most subjects choose D, despite the fact that D is more risky than C. When faced with two choices that both involve losses, individuals seem to behave in exactly the opposite way – they're risk seeking in this case, not risk averse as in the case of A-versus-B.

I used this same example on my article on the behavior of litigants facing settlement decisions[31]. The fact that individuals tend to be risk averse in the face of gains and risk seeking in the face of losses – which Kahneman and Tversky (1979) called "aversion to sure loss" – can lead to some very poor financial decisions. To see why, observe that the combination of the most popular choices, A-and-D, is equivalent to a single lottery ticket yielding $ 240,000 with 25% probability and $ 760,000 with 75% probability, whereas the combination of the least popular choices, B-and-C, is equivalent to a single lottery ticket yielding $ 250,000 with 25% probability and $ 750,000 with 75% probability. The B-and-C combination has the same probabilities of gains and losses, but the gain is $ 10,000 higher and the loss is $ 10,000 lower. In other words, B-and-C is identical to A-and-D plus a sure profit of $ 10,000. In light of this analysis, would you still prefer A-and-D?

A common response to this experiment is that it's unfair because the two pairs of investment opportunities were presented sequentially, not simultaneously. But the fact is that all of us are constantly making decisions about risky choices one after the other, and we don't always have the luxury of contemplating the cumulative effects of those decisions before we make them.

Not surprisingly, the asymmetry between our reactions to monetary gains and losses has a neurophysiological explanation. Camelia M. Kuhnen and Brian Knutson at Stanford University quickly followed up Breiter's experiments with

[30] Tversky died in 1996, otherwise he would no doubt have shared the price with Kahneman.
[31] Abadi, 2019

another fMRI study[32]. Experimental subjects played a computer game Kuhnen and Knutson developed – the Behavioral Investment Allocation Strategy (BIAS) task – while being scanned in the MRI. The players had a choice between three investment options, a "safe" bond or one of two stocks, which moved randomly. Unknown to the players, one of the stocks was a "good" stock, which gained in the long run, and the other, a "bad" stock, which declined in the long run. Additionally, the "good" stock gave a larger long-run reward than the "safe" bond, on average \$ 2.50 per turn versus a consistent \$ 1. Kuhnen and Knutson discovered a very interesting pattern. When players made a risk-seeking mistake – e.g., choosing the "bad" stock over the "good" stock – their nucleus accumbens was activated before they made their decision. Recall that the nucleus accumbens is the same part of the reward circuit that is activated in response to cocaine and monetary gain. In contrast, before players made a risk-averse mistake – e.g., choosing the "safe" bond over the "good" stock – a completely different part of the brain was activated, the anterior insula. This part of the brain is not associated with any reward pathways at all; rather, it seems to be associated with disgust, whether due to an unpleasant odor, or seeing graphic pictures of contamination or bodily mutilation[33]. It seems risk-averse investors process the risk of monetary loss along the same circuit they contemplate viscerally disgusting things, while risk-seeking investors process the risky potential gain along the same reward circuits as cocaine.

[32]Kuhnen and Knutson, 2005. [33]Wicker et al. (2003), Wright et al. (2004)

D The Neuroscience of Rationality

D.A Examples 1

In the mid-1970s, a successful 35-year-old businessman began suffering from intense headaches and a lack of concentration, enough to disrupt his personal and professional life. He was diagnosed with a brain tumor, a meningioma the size of a small orange, which was pressing at his frontal lobes from below. His surgery to remove the tumor was successful, although some frontal lobe tissue was removed as well. His intelligence, his motor skills, and his ability to use language were undamaged in his recovery, but his personality was drastically altered. He lost all sense of proportion at his place of employment, spending the day obsessing over unimportant details while ignoring the most pressing tasks. Deciding what clothes to wear in the morning or what restaurant to dine in at night consumed an inordinate amount of time. He soon lost his job, quickly running through a series of bad business ventures, and then his wife left him. He remarried and then quickly divorced. By the time the neurologist Antonio Damasio encountered him, this man was attempting to get his disability benefits restored; they had been cancelled since his mental and physical abilities were, in the opinion of other doctors, still intact. The man was, to all external appearances, a "malingerer"[34]. Damasio was doubtful. The new imaging techniques of the time – computerized tomography (CT), magnetic resonance imaging (MRI), and single-photon emission computed tomography (SPECT) – were used to scan the patient's brain. They revealed very localized lesions on the left and right frontal lobes of his cortex. The man – the neurological literature refers to him as "patient E.V.R." , but Damasio in his book *Descartes' Error* gives him the pseudonym "Elliot" – only had a small portion of his brain damaged, the ventromedial prefrontal cortex, located a few centimeters behind the lower forehead. Damasio theorized that this small section of the brain was involved in the higher function of decision-making.

However, unlike other patients with frontal-lobe damage, Elliot performed normally on specialized psychological and personality tests. After extensive conversations with him, however, Damasio began to believe there was something else missing besides his ability to make good decisions. Although a pleasant, even witty, conversationalist, Elliot showed very little emotional affect talking about his misfortunes. As Damasio probed further, he found that Elliot was almost always on a seemingly even emotional keel: never sad, never anxious, never impatient, and only very briefly angry. Psychological tests measuring physiological reactions to violent imagery confirmed this deficit. After one series of tests, Elliot himself confirmed this change to Damasio: "topics that had once evoked a strong emotion no longer caused any reaction, positive or negative" . Damasio tentatively called this set of conditions "acquired sociopathy"[35]. Apparently, this loss of emotional faculties had a surprisingly profound effect on Elliot's day-to-day activities, as Damasio (1994) describes:

[34] Damasio (1994), Eisinger and Damasio (1985).

[35] Damasio (1994), Saver and Damasio (1991), Damasio, Tramel, and Damasio (1991, 1998).

When the job called for interrupting an activity and turning to another, he might persist nonetheless, seemingly losing sight of his main goal. Or he might interrupt the activity he had engaged, to turn to something he found more captivating at that particular moment... The flow of work was stopped. One might say that the particular step of the task at which Elliot balked was actually being carried out too well, and at the expense of the overall purpose. One might say that Elliot had become irrational concerning the larger frame of behavior . . .

Elliot's inability to feel – his lack of emotional response – somehow caused him to make irrational choices in his daily decisions. This conclusion surprises many economists because of the association between emotion and behavioral biases. After all, isn't it fear and greed, or "animal spirits" as Keynes once suggested, that cause prices to deviate irrationally from "fundamentals"? In fact, a more sophisticated view of the role of emotions in human cognition is that they are central to rationality[36]. Emotions are the basis for a reward-and-punishment system that facilitates the selection of advantageous behavior, providing a numeraire for animals to engage in a "cost-benefit analysis" of the various actions open to them (Rolls, 1999). Even fear and greed the two most common culprits in the downfall of rational thinking, according to most behavioralists – are the product of evolutionary forces, adaptive traits that increase the probability of survival. From an evolutionary perspective, emotion is a powerful tool for improving the efficiency with which animals learn from their environment and their past. When an individual's ability to experience emotion is eliminated, an important feedback loop is severed and his decision-making process is impaired.

D.B Examples 2

The complexity of the interactions among the distinct components of the brain may be illustrated by two examples. The first involves the difference between a natural smile and a "forced" smile (see Damasio, 1994), which is easily detected by most of us, but why? The answer lies in the fact that a natural smile is generated by one region of the brain – the anterior cingulate – and involves certain involuntary facial muscles that are not under the control of the motor cortex. The forced smile, however, is a purely voluntary behavior emanating from the motor cortex, and does not look exactly the same because involuntary

[36]See, for example, Damasio (1994) and Rolls(1990, 1994, 1999). Recent research on the cognitive neurosciences and economics suggest an important link between rationality in decision-making and emotion (Grossberg and Gutowski, 1987; Damasio (1994; Elster, 1998; Lo, 1999; Lo and Repin, 2002; Lowenstein, 2000; and Peters and Slovic, 2000), implying that the two are not antithetical, but in fact complementary. For example, contrary to the common belief that emotions have no place in rational decision-making processes, Lo and Reoin (2002) present preliminary evidence that the physiological variables associated with the autonomic nervous system are highly correlated with market events even for highly experienced professional securities traders. They argue that emotional responses are a significant factor in the real-time processing of financial risks, and that an important component of a professional trader's skill lies in his or her ability to channel emotion, consciously or unconsciously, in specific ways during certain market conditions.

muscles do not participate in this action. In fact, it takes great effort and skill to generate particular facial expressions on cue, as actors trained in the "method" school can attest – only by conjuring up emotionally charged experiences in their past are they able to produce the kind of genuine emotional reactions needed in a given scene, and anything less authentic is immediately recognized as "bad acting" . The second example is from a study by Eisenberger, Lieberman, and Williams (2003) in which they deliberately induced feelings of social rejection among a group of subjects and then identified the regions of the brain that were most activated during the stimulus. They discovered that two components were involved, the anterior cingulate and the insula, both of which are also known to process physical pain. In other words, emotional trauma – hurt feelings, emotional loss, embarrassment, and shame – can generate the same kind of neural response that a broken bone does. Many who have experienced the death of a loved one have commented that they felt *physical* pain from their loss despite the fact that no physical trauma was involved, and we are now beginning to develop a neuroscientific basis for this phenomenon. Eisenberger, Lieberman, and Williams (2003) conclude that ". . . social pain is analogous in its neurocognitive function to physical pain, alerting us when we have sustained injury to our social connections, allowing restorativemeasures to be taken"

These two examples illustrate some of the many ways in which specialized components in the brain can interact to produce behavior. The first example shows that two different components of the brain are capable of producing the same outcome: a smile. The second example shows that the same components can be involved in producing two different outcomes: physical and emotional pain. The point of specialization in brain function is increased fitness in the evolutionary sense. Each specialized component may be viewed as an evolutionary adaptation designed to increase the chances of survival in response to a particular environmental condition. As environmental conditions change, so too does the relative importance of each component. One of the unique features of *homo sapiens* is the ability to adapt to new situations by learning and implementing more advantageous behavior, and this is often accomplished by several components of the brain acting together. As a result, what we call "preferences" are often complicated interactions among the various components of the brain.

This perspective implies that preferences may not be stable through time, but are likely to be shaped by a number of factors, both internal and external to the individual, i.e., factors related to the individual's personality, and factors related to specific environmental conditions in which the individual is currently situated. When environmental conditions shift, we should expect behavior to change in response, both through learning and, over time, through changes in preferences via the forces of natural selection. These evolutionary underpinnings are more than simple speculation in the context of financial market participants. The extraordinary degree of competitiveness of global financial markets and the outsized rewards that accrue to the "fittest" traders suggest that Darwinian selection is at work in determining the typical profile of the successful investor. After all, unsuccessful market participants are eventually eliminated from the population after suffering a certain level of losses.

Since Damasio's pathbreaking studies of the role of emotion in rational and irrational behavior, several of Damasio's students and colleagues at the University of Iowa have developed new tests for patients with similar neuropathologies. Antoine Bechara, then Damasio's postdoctoral student, devised what is now called the Iowa Gambling Task[37]. This psychological test takes some of its inspiration from Daniel Kahneman and Amos Tversky's experiments, but Bechara wanted to use as realistic a decision-making task as possible, so he turned to that very common pastime, a deck of cards.

In the basic task, the experimental test subject – called the "player" – is seated in front of four decks of cards and is given \$ 2,000 in realistic-looking play money. The object of the game is to lose as little money and gain as much money as possible. The player turns a card selected from any one of the decks, and either wins or loses a certain amount of money for each turn. What the player does not know beforehand, of course, is that the decks are rigged. Decks A and B pay \$ 100 for each turn of a card, but deck A will occasionally cost the player a few hundred dollars – enough so that a pure strategy from deck A will deplete their stake – and deck B will less frequently penalize the player \$ 1,250 dollars. Decks C and D, on the other hand, pay \$ 50 per turn, with deck C occasionally penalizing the player a small amount, \$ 25 or \$ 50 or \$ 75, and deck D infrequently penalizing the player \$ 250, but never enough to cause a loss in the long run. Regular players – that is, the control group – typically start off the game by trying out cards from each of the four decks. Then, lured by the promise of a larger payoff, they focus on decks A and B, until they realize this is not a winning strategy. This typically happens within the first thirty cards. The player then switches to decks C and D, although some risk-takers will still occasionally sample cards from decks A and B as well. This continues on for a hundred cards, which is when the croupier/experimenter calls a halt to the test. Players with damage to their ventromedial prefrontal cortex or their amygdala employ a completely different strategy from the control group. They start off in the same way, sampling the decks, but as the game continues they prefer decks A and B over decks C and D, despite the fact that those decks are designed to bankrupt the player. When the player inevitably goes bankrupt, the experimenter loans them more money. Even frontal patients who describe themselves as "low-risk" will systematically choose decks A and B much more often than regular players who describe themselves as "high-risk"[38]. Without certain emotional faculties, the ability to process risk is clearly impaired. This finding suggests that emotion plays a critical role in producing rational trade-offs between risk and reward, which is the crux of financial decision-making.

[37]Bechara et al., 1994. [38]Damasio, 1994.

E The Neuroscience of Sentience

In the early 1990s, a chance discovery by a group of researchers at the University of Parma led by Giacomo Rizzolatti showed that perhaps the "theory of mind" was not very abstract at all, but hardwired into the structure of the brain itself[39]. Using recording microelectrodes generations more advanced than the ones used in Olds and Milner's experiment, Rizzolatti and his group found there were specific neurons in the macaque monkey brain that responded to "mirrored" motions in others. For instance, a certain neuron in the premotor cortex would fire when a macaque grasped an object as well as when an experimenter grasped an object. This was direct physical evidence that the macaque could understand the actions of others in terms of its own experience, even across species. In short, the macaque had a basic "theory of mind" hardwired into its neurophysiology. This discovery of "mirror neurons" was entirely unexpected. While some neuroscientists had jokingly spoken of "grandmother neurons", neurons that would fire when individuals saw their grandmothers, no neurologist expected a basic system in the brain for understanding the behavior of others in terms of one's own physical actions. In fact, the discovery was so out of left field that the prestigious scientific journal *Nature* declined to publish Rizzolatti's manuscript because its editors believed it lacked "general interest"[40]. This rejection notwithstanding, in a short time Rizzolatti and his team detected mirror neurons in humans as well, not through the use of microelectrodes, but through the use of positron emission tomography (PET), which showed neural activity in the analogous areas of the human brain as in the macaque in response to mirrored behavior. Like our evolutionary cousins, we humans have neurons that automatically "light up" in sympathy to the actions of others. That sympathy phenomenon is the genesis of the "crowded trade" behavior which amplifies booms and busts alike.

Now in contrast to the common neuroscientific approach of determining the function of parts of the brain by studying the behavior of individuals in whom such parts are damaged, in the case of mirror neurons, the approach has been reversed. We know what the neurons do, but we don't yet know how they affect behavior. One hypothesis, proposed by Rizzolatti and others, is that a deficit in the brain's mirror mechanism may be involved in autism spectrum disorder, that complex syndrome of learning, social, communicative, and emotional deficits. People with autism often have difficulty in understanding other people's motives and, therefore, connecting socially, suggesting they have an undeveloped theory of mind, as the British neuroscientist Simon Baron-Cohen believes[41]. Here, however, we don't have to look for specific neurological case studies among autistic children. Every one of us has, as children, passed through life stages where our own theories of mind were undeveloped.

It is strange to think that at some point before the age of four, we were not able to understand that another person, perhaps a parent, could believe something that we ourselves knew was not true. As adults, of course, most of us

[39]Di Pellegrino et al., 1992. [40]Rizzolatti and Fabbri-Destro (2010). [41]Baron-Cohen, 1989.

are comfortable with the idea that other people might be mistaken. For those of us who are parents, the knowledge that a child under the age of four is mentally incapable of understanding this is vaguely comforting, particularly when we are faced with what looks like otherwise unreasonable behavior. However, by the time most children reach the age of four, they are able to deal with what psychologists call "first-order false belief". Sentimentally, we might pinpoint that age as the time when we learn that our parents aren't infallible, but in reality, that's the age our brains have developed to the point where we can understand that other people can be fallible. It's an important step on the pathway to a full "theory of mind". In fact, a four-year-old might be able to understand a statement like, "David thinks his birthday present is in red wrapping, but the present is really in the green wrapping". But a typical four-year-old would not understand a statement like, "Elizabeth thinks David thinks his birthday present is blue, and David thinks his birthday present is red, but it's really green". The ability to understand a second-order false belief, instead of following naturally and recursively from the ability to understand a first-order false belief, takes a few more years to develop. In general, a seven-year-old can understand a story with a second-order false belief. This means their theory of mind is rich enough not only to model another person's mental state, but also to model another person's model of a person's mental state. A four-year-old can see one mirror deep into the hall of mirrors of intention, while a seven-year-old can see two mirrors deep[42].

[42] Perner and Wimmer, 1985.

F The Neuroscience of Interactions

F.A Pain-Avoiding Circuitry Override

However, the behavior of *homo sapiens* can be considerably more subtle, as illustrated by the remarkable story of the 27-year-old mountain climber Aron Lee Ralston, whose ordeal was chronicled in the gripping film *127 Hours*. On April 26, 2003, Ralston was climbing a 3-foot wide crevasse in Bluejohn Canyon in a remote region of southeastern Utah when an 800-pound boulder slipped and pinned his arm to the wall of the crevasse. He was trapped in the crevasse for five days, and he finally escaped by amputating his right arm below the elbow with a dull knife. This story is incredible because we recognize that Ralston voluntarily inflicted extraordinary pain on himself, in direct contradiction to our most basic instinct of pain avoidance. How was he able to accomplish this feat? Presumably, he was able to override his pain-avoidance circuitry by creating an alternate scenario in his mind that was considerably more rewarding – despite the fact that it included the painful amputation – than dying alone in the crevasse on that day. While extraordinary, Ralston's feat proves that investors (whose choices are far less stark than Ralston's) can override their pain-avoiding circuitry (e.g., the reluctance to take losses early) by creating alternate, more rewarding, scenarios.

Our capacity to create complex scenarios, pure figments of our substantial imaginations, is one of the most important evolutionary advantages we've developed, and it seems to be unique to our species. The portion of the brain responsible for these complex thoughts is known as the prefrontal cortex, and while similar structures do exist in other mammals, *homo sapiens* seems to have the largest and most highly connected version[43]. Neuroscientists have shown that many of the uniquely human traits such as language, mathematical reasoning, complex planning, self control, and delayed gratification originate in the prefrontal cortex. For this reason, this region is sometimes referred to as the "executive brain" . Like the CIO of a well-run hedge fund, the prefrontal cortex is responsible for developing a portfolio of strategies for the fund, monitoring the performance of the strategies, and making resource-allocation decisions that weigh the costs and benefits of each competing portfolio manager's goals so as to maximize the chances of achieving the overall objectives of the firm while protecting it from current and potential threats. This asset management hierarchy is not simply a useful analogy – it's actually part of our neurophysiology[44]. This "command-and-control center" was the region of the brain destroyed in Phineas Gage's unfortunate accident, with predictable consequences. The executive functions that human brains possess allow us to engage in far more complex behaviors than other species. A simple manifestation of this difference is the fact that we can more easily predict the behavior of other animals than those of humans. Great white sharks circle their prey before striking, Canadian geese migrate south during the winter, and ocean-dwelling Pacific salmon return to freshwater rivers to lay their eggs. While humans exhibit certain predictable

[43]Schoenemann et al. (2005) and Smaers et al. (2011). [44]Botvinick, 2008.

traits as well (a significant fraction of New Yorkers also migrate south for the winter), the number of possible behaviors generated by the prefrontal cortex is exponentially greater, simply because of our ability to imagine and choose from a multitude of hypothetical realities. Many of these alternate realities are highly elaborate what-if scenarios that can move us to do extraordinary things. According to Aron Ralston, it was the following hypothetical reality that allowed him to do the unthinkable[45]:

A blond three-year-old boy in a red polo shirt comes running across a sunlit hardwood floor in what I somehow know is my future home. By the same intuitive perception, I know the boy is my own. I bend to scoop him into my left arm, using my handless right arm to balance him, and we laugh together as I swing him up to my shoulder… Then, with a shock, the vision blinks out. I'm back in the canyon, echoes of his joyful sounds resonating in my mind, creating a subconscious reassurance that somehow I will survive this entrapment. Despite having already come to accept that I will die where I stand before help arrives, now I believe I will live. That belief, that boy, changes everything for me.

Ralston was not married or engaged at that time, and had no children. In August 2009, Ralston married Jessica Trusty, and their first child, Leo, was born in January 2010.

F.B Prefrontal Cortex Limitations

As impressive and unique as the human prefrontal cortex is, it can't operate instantaneously or indefinitely. In fact, in certain circumstances, it doesn't operate at all. For example, individuals who faint when confronted with shocking news do so through a sudden loss of blood pressure that shuts down the prefrontal cortex, causing them to lose consciousness. A less extreme illustration of the limitations of the prefrontal cortex is "decision fatigue" , a phenomenon recently documented among a group of judges presiding over parole hearings for Israeli prisoners. During each day of hearings, there were two food breaks that divided the day into three distinct sessions, and researchers found a striking pattern over these sessions: the judges rendered favorable parole decisions about 65% of the time at the start of these sessions, but the percentage would systematically decline to nearly 0% by the end of each session[46].It appears that difficult decisions can be mentally taxing in some manner, so as these sessions wore on, the judges became more inclined to avoid such decisions by denying parole. However, after the food breaks (a late-morning snack, and then a lunch break), the judges were refreshed and ready to resume their complex deliberations; hence parole rates at the beginning of the following session were considerably higher. The fact that the increased parole rates followed food breaks is consistent with recent findings that glucose can reverse the effects of decision fatigue[47]. Apparently, it really is true that one should never trade on an empty stomach.

[45]Ralston, 2004. [46]See Danziger, Levav, and Avnaim-Pesso (2011). [47]Tierney, 2011

F.C The Behavioral Life-Cycle Model

As with those hedge fund CIOs who lead their firms astray, there are many paths to failure. Early behavioral models of economic choice recognized these pathologies and modeled their effects explicitly to produce more realistic consumer saving and spending patterns, such as the "behavioral life-cycle model" of Hersh Shefrin and Richard Thaler[48]. These insights led to a significant innovation in retirement savings plans, pioneered by Shlomo Benartzi and Thaler – the idea of allowing participants to "opt out" instead of asking them to "opt in", and reducing the number of choices so they don't over-diversify into investments that they don't really understand or want[49]. These seemingly superficial changes can have huge positive impact on the participation rate of 401(k) plans, which everyone agrees is a good thing. In one empirical study, participation rates for the standard opt-in plan was around 20% after three months of employment and increased gradually to 65% after 36 months; with automatic enrollment, the participation rate of new employees jumped immediately to 90% , and the fact that participation increased to 98% after 36 months suggests that few individuals opted out[50]. Not only did this simple change increase the participation rate, it also caused employees to join sooner, which obviously benefits long-term wealth creation.

[48]Shefrin and Thaler (1988). [49]Benartzi and Thaler (2004). [50]Mandrian and Shea (2001).