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ABSTRACT

Mind, Body, Bubble! Psychological and Biophysical Dimensions of Behavior in Experimental Asset Markets

Asset market bubbles and crashes are a major source of economic instability and inefficiency. Sometimes ascribed to animal spirits or irrational exuberance, their source remains imperfectly understood. Experimental methods can isolate systematic deviations from an asset's fundamental value in a manner not possible on the trading floor. In this chapter, we review evidence from dozens of laboratory experiments that investigate the measurement and manipulation of an array of psychological and biophysical attributes. Measures of emotion self-regulation and interoceptive ability are informative, as is cognitive ability and the level and fluctuation of hormones. Rules that promote deliberative decision making can improve market efficiency, while incidental emotions can impair it. Signals in specific brain areas can be a trigger precipitating a bubble's collapse. We conclude that trading decisions are profoundly biophysical in a manner not captured by efficient markets models, and close with speculations on implications for algorithmic trading.

JEL Classification: C92, D91, G12, G41

Keywords: efficient markets hypothesis, emotions, experimental asset markets, price bubbles and crashes, somatic marker hypothesis

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Introduction[*]

The role of financial markets is to source capital for business investment and allocate risks to those best placed to bear it. The performance of these markets has profound implications for efficiency, stability, and the distribution of wealth in the economy. Yet the success of real-world markets in serving these functions has been hotly debated since the time of the Great Depression. On one side, the Efficient Markets Hypothesis (EMH) of Fama (1970) asserts that asset prices fully reflect market fundamentals. However, others have argued that human psychology and emotions exercise an enormous influence over financial decision making, in a manner abstracted from in standard theory. Thus Keynes (1936) speaks of 'animal spirits', and Shiller (2000) of 'irrational exuberance', as distortionary influences upon asset prices. While both interpret such influences to be negative, emerging research suggests that our emotions may be an integral, even essential, component of human decision making in the face of risk. In this chapter, we review recent research that uses laboratory experimental methods to explore the influence of psychological and biophysical variables on decision making in financial markets.

Participation in financial markets exposes individuals to tradeoffs between risk and reward, and this is true not only for market professionals, but also for retail investors who face important choices involving their investment, borrowing, and retirement savings. Decision making in such settings is difficult and reflects a complex combination of forces. Factors that are emphasized in standard economics and finance include market institutions (such as access to futures markets and constraints on short-selling); incentive and information structures; the risk, time and ambiguity preferences of market participants as well as their beliefs and expectations; and strategic uncertainty over the preferences and rationality of others. To this list, we can add features emphasized in behavioral finance and psychology such as cognitive limitations, self-control and emotions, as well as biophysical phenomena such as hormones and neural activity.

Under the EMH, asset prices fully reflect all available information; psychological and biophysical states of traders should not distort how that information is processed, and should have no direct predictive power. According to this standard view, a more rational trader could exploit a market participant who relied unduly upon emotions or 'gut feelings', profiting at the latter's expense. In contradiction to the EMH, however, it is widely believed that asset prices at times deviate considerably from their fundamental value (FV, also known as intrinsic value), with market psychology implicated as a driving force behind such deviations. A bubble in asset prices is defined as

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‘trade in high volume at prices that are considerably at variance from intrinsic value’ (King et al., 1993, p. 183). Such a bubble, as well as its ensuing and ultimately inevitable crash, has tremendous societal implications including misallocation of capital, propagation of instability to the real economy, and redistribution of wealth.

Studying financial markets using observational data is difficult because the researcher cannot observe, let alone control, all relevant variables – most notably the FV of the assets that are bought and sold. When FV is unobservable, researchers may disagree over whether a bubble has occurred, even in hindsight (see Thompson, 2006, arguing that there was no Dutch tulip bubble, and Pástor and Veronesi, 2006, arguing that there was no dot-com bubble). This motivates a long tradition of using laboratory experiments to study the efficiency of market outcomes (Chamberlin, 1948; Smith, 1962; Smith et al., 1988). These experiments allow a researcher to control key variables and generate repeated observations under identical conditions. Since FV is under the control of the experimenter, price bubbles can be precisely quantified, and are in fact commonly observed. This is particularly the case in the paradigm introduced by Smith, Suchanek and Williams (Smith et al., 1988; SSW), described in more detail below, which is the focus of this chapter.

The literature using SSW experiments initially focused on evaluating the effects of market institutions, incentives and information on market behavior (see Palan, 2013, for a review). This research proved somewhat unsatisfactory in that even after several decades of study, there remains considerable, indeed extraordinary, unexplained heterogeneity in behavior, both between markets under the same conditions and between individuals within a given market.

Experiments can be used not only to study traditional finance variables, but also to manipulate the mix of characteristics of market participants, and to measure their psychological and biophysical states. In this chapter, we review an emerging literature, almost all dating from the past five years, that shifts the focus of research onto the characteristics of the individuals who populate experimental markets. These characteristics include basic individual differences such as gender, traditional psychological variables such as cognitive ability, and other personality measures such as theory of mind (ToM, essentially the ability to attribute mental states to others). We also consider measures of changeable biophysical characteristics of a given individual, such as facial expression, levels of steroid hormones (e.g., testosterone and cortisol), measures of neural activity derived from fMRI techniques, and self-reported emotional states. Our review highlights how an array of tools to measure subjects’ characteristics and emotional and biophysical states can be used, and can complement one another, in understanding the nucleation, expansion and collapse of price bubbles.

The role of the brain-body nexus in financial decision making

Alongside the casino, asset markets are the classic environment in which substantial risks and rewards confront participants. Indeed, Coates and Gurnell (2017) assert that 'financial markets present us with the largest and most intense competitive forum ever constructed'. In economics and finance, the standard account of rational choice in financial markets is epitomized by the Efficient Markets Hypothesis (EMH) which proposes that 'security prices at any time "fully reflect" all available information' (Fama, 1970, p. 383). Critics of this account suggest that it requires traders to routinely solve optimization problems that are computationally infeasible, even with unlimited processing capacity (Bossaerts & Murawski, 2017). It also describes a world of 'disembodied' traders, in which the rational mind makes decisions without input from the body in which, and with which, it evolved.

The embodied mind

Damasio's book *Descartes' Error* (1994) was the first to show how the anticipation of risk and reward activates and integrates the 'soma', or body, in risky decisions. Patients with brain lesions preventing interoceptive access to somatic signals (our conscious and unconscious sensitivity to internal bodily sensations), but who were otherwise normal, experienced dramatic declines in decision quality, leading Damasio to develop the 'somatic marker hypothesis'. Somatic signals can assist fast and instinctive decision making of the type classified by Kahneman (2011) as 'System 1 thinking', bypassing the kinds of deliberate cognitive engagement that standard theory takes to be our only method for choosing ('System 2 thinking'). While Kahneman emphasizes the potential bias that can arise from relying on System 1 alone, Damasio focuses instead on the visceral knowledge that System 1 can bring and he argues that it most often leads to improved decision making under risk. This new 'risk as feelings' paradigm was further developed by Loewenstein et al. (2001).

Without somatic signals, a trader will struggle to avoid high-variance but negative expected value alternatives (Bechara & Damasio, 2005). Although such traders would use 'all available information' as the EMH presumes, they would be doing so without access to somatic or other emotional responses to the situation. Our emotional reactions are sensitive to a wider range of features of the decision environment than are System 2's cognitive evaluations alone. This implies that efforts to 'prime' traders with emotionally laden stimuli prior to trading can influence subsequent market outcomes in a manner inconsistent with standard theory.

The inevitable involvement of the soma in traders' decisions is vividly described by neuroscientist and former Wall Street trader John Coates, in his 2012 book *The Hour between Dog and Wolf: Risk*

Taking, Gut Feelings and the Biology of Boom and Bust. He dramatizes the somatic effects on traders of an impending announcement by the US Federal Reserve as follows (p. 2):

> Scott and Logan's bodies, largely unbeknownst to them, have also prepared for the event. Their metabolism speeds up, ready to break down existing energy stores in liver, muscle and fat cells should the situation demand it. Breathing accelerates, drawing in more oxygen, and their heart rates speed up … their nervous system, extending from the brain down into the abdomen, has begun redistributing blood throughout their bodies, constricting blood flow to the gut, giving them the butterflies …
>
> As the sheer potential for profit looms in their imaginations, Scott and Logan feel an unmistakable surge of energy as steroid hormones begin to turbo-charge the big engines of their bodies. These hormones take time to kick in, but once synthesized by their respective glands and injected into the bloodstream, they begin to change almost every detail of Scott and Logan's body and brain – their metabolism, growth rate, lean-muscle mass, mood, cognitive performance, even the memories they recall …
>
> Scott and Logan's testosterone levels have been steadily climbing. This steroid hormone, naturally produced by the testes, primes them for the challenge ahead, just as it does athletes preparing to compete and animals steeling for a fight. Rising levels of testosterone increase Scott and Logan's hemoglobin, and consequently their blood's capacity to carry oxygen; the testosterone also increases their state of confidence and, crucially, their appetite for risk. For Scott and Logan, this is a moment of transformation, what the French since the Middle Ages have called 'the hour between dog and wolf'.
>
> Another hormone, adrenalin, produced by the core of the adrenal glands located on top of the kidneys, surges into their blood. Adrenalin quickens physical reactions and speeds up the body's metabolism, tapping into glucose deposits, mostly in the liver, and flushing them into the blood so that Scott and Logan have back-up fuel supplies to support them in whatever trouble their testosterone gets them into. A third hormone, the steroid cortisol, commonly known as the stress hormone, trickles out of the rim of the adrenal glands and travels to the brain, where it stimulates the release of dopamine, a chemical operating along neural circuits known as the pleasure pathways … An expectant hush descends on global markets.

Somatic signals influence behavior by biasing their decision process toward or away from particular options (Bechara & Damasio, 2005). The brain's ventromedial prefrontal cortex (vmPFC), a center of rational thought, remains crucial for associating one's emotional state with any complex decision

(Poppa & Bechara, 2018). However, numerous other brain regions, such as the amygdala, provide the visceral responses integrated by the vmPFC (Poppa & Bechara, 2018). The most critical conduit for these somatic signals is not the spinal cord but the vagus (or 'wandering') nerve. The vagus nerve has 'efferent' fibers to transmit messages from the brain stem to the body, including the enteric nervous system (also known as our 'gut brain' or 'second brain'), and 'afferent' fibers carrying nerve signals from the body back to the brain stem, in a constant two-way chatter (Maniscalco & Rinaman, 2018). These signals to the lower brain stem (in particular, the caudal nucleus tractus solitarius or cNTS) stimulate the release of neurotransmitters such as dopamine, serotonin, noradrenaline (epinephrine) and acetylcholine that affect our central nervous system. Bechara and Damasio (2005) describe how these neurotransmitters then modulate the synaptic activity underpinning our choice behavior, until the dominant somatic state exerts its preferred biasing effect upon our decisions.

The cNTS is a key part of the brain's dorsal vagal complex, the central node for receiving interoceptive information from the soma, particularly the gut (Maniscalco & Rinaman, 2018). In a recent survey of this literature, Poppa and Bechara (2018) note that 'the evidence strongly suggests that visceral processes mediated by afferent vagus nerve signalling participate in shaping higher-order cognition', indicating a central role for the vagus nerve in making advantageous decisions under risk. Vagal efferent effects on heart rate can occur within milliseconds, easily fast enough to impact traders' decisions.

If EMH holds true, biophysical measures of market participants cannot explain bubbles and crashes, nor can they predict the relative success of traders. However, contrary to EMH, human traders' interpretation of 'all available information' can subconsciously skew toward *either* opportunity *or* risk, rather than a dispassionate assessment of both. Coates (2012) argues that excitement and fear manifest as shifts in confidence and risk preferences, caused by changes in circulating levels of testosterone (for reward) and cortisol (for risk). While testosterone sharpens responses, and boosts the confidence of male traders, a bear market may raise traders' levels of cortisol, exacerbating existing risk aversion that then deepens the downturn. The role of testosterone in female decisions has not been extensively studied to date; we return to this issue below.

While serotonin influences our choices with conscious awareness, not all somatic signals accessible to us by interoception manifest consciously. The effects of other steroids, such as testosterone's effect on dopamine transmission in the nucleus accumbens (NAcc), manifest subconsciously. In this way, our choices can reflect the information content of these signals even before we can articulate why we choose as we do (Bechara & Damasio, 2005).

We can measure the arousal triggered by risk and reward in many ways. These include skin conductance response (SCR), which measures changes in electrical conductance, heart rate, and heart rate variability (HRV). Some changes to our musculoskeletal system may be noticeable to others, such as our facial expressions, making them accessible to categorization (Darwin, 1872; Colzato et al., 2017), most recently using face-reading software. Facial expressions do not cause behavior, but they are a convenient biomarker of the deeper visceral antecedents produced by the brain-body nexus when we face dynamic risk-reward environments. When our somatic responses to market conditions produce emotions, our facial expressions take on predictable patterns. For this reason, professional poker players go to great lengths to mask their reactions from other players as play unfolds.

Levenson (2014) reviews the evidence for coherence in how different parts of our autonomic nervous system react to emotion-laden stimuli. He describes one study that measured subjects' SCR, heart rate and facial muscle movements in response to an image intended to provoke disgust. Each of the measures responded rapidly and coherently, despite exhibiting no correlation prior to the stimulus. Mauss et al. (2005) also find strong evidence for coherence across very different response measures. For example, a film evoking sadness produced within-subject lagged correlation coefficients between facial expression and SCR of $r = -0.52$ and between facial expression and emotional self-reports of $r = 0.74$. This result is reassuring for researchers using emotional self-reports rather than, or in addition to, biophysical measures.

Inter-personal differences

A growing number of psychological traits and capacities are now known to have specific and measurable biophysical manifestations. In an echo of nineteenth century phrenology, Riccelli et al. (2017) found the Big Five personality traits of a large sample of 507 subjects to have measurable correlates in the morphology of their prefrontal cortices. Theory of mind (or 'social intelligence') is also localized in the human brain. A recent meta-analysis of relevant fMRI studies found BOLD signals from the posterior region of the right temporal parietal junction (rTPJ) to be an independent region (distinct from the anterior rTPJ), isolated for this purpose (Krall et al., 2015). Deficits in social cognition (e.g., autism spectrum disorders) are associated with abnormal function of the posterior rTPJ (Pantelis et al., 2015). Luders et al. (2009) and Menary et al. (2013), inter alia, find significant connections between measures of general intelligence and the size and structure of some brain areas. In particular, the size of the mid-saggital corpus callosum, which connects the two brain hemispheres, is positively associated with cognitive ability.

The effect of (changes in) hormone levels on decisions is not straightforward. For example, we can measure the organizational effects of pre-natal androgen exposure using the ratio of lengths of our second and fourth fingers (2D:4D ratio), particularly of the right hand, which correlates with risk preference within, but not across, ethnicities (e.g., Brañas-Garza & Rustichini, 2012, and references therein). Inter-personal differences in biophysical characteristics, such as circulating steroid hormone levels and within-person shifts in these levels over time, can each induce systematic shifts in attitudes to the same information, contrary to EMH, leading to different actions. For example, some research suggests that both a 'sufficiently male' brain structure (of a type possessed by only some males, and no females) *and* a sufficient amount of circulating testosterone are necessary for changes in testosterone levels to lead to shifts in utilities, confidence and risk preferences (Coates et al., 2010; Nadler et al., in press).

Turning to gender differences, biophysical measures such as brain size and organization can be difficult to interpret, given the many kinds of sexual dimorphism in humans. For example, if investigating the effects of baseline circulating testosterone levels on trading behavior, it would be foolish to classify women as very low testosterone men and expect the results to be meaningful. Furthermore, the effects of testosterone and other hormones on differences in behavior between men and women is under-researched.

One explanation for this dearth of research is that female hormone levels differ pre-and post-menarche and menopause, and over the estrus cycle, making it less complicated to focus on males (Maniscalco & Rinaman, 2018). For example, there are no experiments investigating the impact of the phase within the estrus cycle of female traders on asset price trajectories, even though such studies should be feasible. This lack of research examining biophysical measures of gender differences leaves us with few predictions for gender differences in behavior, even though gender differences are among the most profound of all inter-personal differences.

Damasio's early work comparing lesion patients with controls treated interoceptive ability as a characteristic that an individual either possesses or does not possess. The evidence today is that interoceptive abilities are distributed along a continuum, from Damasio's lesion patients at one extreme, to the most successful high-frequency traders at the other (Kandasamy et al., 2016). By far the most common measure of interoceptive ability today is drawn from the heart rate detection task, following its successful generalization to the detection of other internal somatic responses (Critchley & Garfinkel, 2015). Electrocardiography can separate two bands of heart rate variability (HRV): low frequency (LF) and high frequency (HF). The magnitude of the difference in HF HRV between systolic and diastolic phases is the best measure of how the ongoing activity of the vagus nerve (or 'vagal tone') is instantiated. It provides our best measure of moment-to-moment emotional self-regulation, which operates primarily via the neurotransmitter acetylcholine (Fenton-O'Creevy et al., 2012). This HF HRV is arguably a key measurable biophysical characteristic that can identify one's position along the continuum of interoceptive ability; higher values indicating better emotional regulation and interoceptive ability, and low values associated with the opposite (Appelhans & Luecken, 2006).

It has recently become possible to stimulate the afferent fibers of the vagus nerve to enhance somatic signaling into the central nervous system, cheaply and non-invasively, using transcutaneous vagus nerve stimulation (tVNS) applied to the left ear (see Poppa & Bechara, 2018). Stimulation is known to produce BOLD signal changes detected by fMRI in several brain regions including the cNTS (ibid.). New placebo-controlled research using tVNS to stimulate vagal tone shows the vagus nerve to be causally involved in creativity. By stimulating vagal afferent fibers, there is an increase in the steroid hormone epinephrine and the inhibitory neurotransmitter, gamma-amino butyric acid (GABA). These biophysical changes regulate our fear and anxiety response to a stimulus, such as falling stock prices: our ability to self-regulate our emotional responses diminishes if our GABA level is low (Colzato et al., 2018). Another possibility is to wear a device called a 'Doppell' on one's wrist that sends a constant heartbeat-like vibration to the inner wrist. Unlike the activity of the tVNS device, the wearer perceives the Doppell's vibrations. Early placebo controlled research finds that this device successfully reduces the wearer's emotional reactivity in stressful environments (Azevedo et al, 2017).

In summary, and contrary to the EMH, what happens in vagus does not stay in vagus. By stimulating specific patterns of neurotransmitter release from the brain stem, the flow-on effects of vagal afferent signals ensure that markets are composed of 'embodied', and not 'disembodied', traders. In consequence, it is possible to measure, manipulate and sort individuals by specific biophysical characteristics that we now know to influence decisions under risk. The studies that we review henceforth in this chapter focus on some pieces of the puzzle that help to further our understanding of the root causes of instability in financial markets.

Experimental environment

We focus in this review on asset market experiments that build upon the paradigm introduced by Smith, Suchanek and Williams (Smith et al., 1988; SSW), broadly interpreted. In these experiments, each participant receives an initial endowment of experimental money and 'shares', which may be bought and sold in a market over several periods. Shares are assets which yield income in the form of dividends in each period. They have a finite lifetime, such that as the experiment progresses there are fewer dividends remaining, meaning that each share's risk-neutral fundamental value (FV, which is the expected dividend per period multiplied by the number of outstanding dividends) declines over time. Since dividends have the same value to all traders, who are symmetrically informed, standard theory predicts that all trades should be priced at FV.

Since FV is induced by the experimenter, deviations from it can be precisely quantified, which is not the case in naturally-occurring markets. We distinguish two broad forms of deviation. First, measures of *overvaluation* (such as the Relative Deviation, or RD) capture the extent to which market prices tend to be above or below FV on average. In this type of measure, periods of positive and negative deviation cancel out. Second, measures of *mispricing* (such as the Relative Absolute Deviation, or RAD) capture the extent of absolute deviation from FV, without regard for sign. This type of measure penalizes all positive and negative deviations alike. In our review we focus primarily on market-level measures of overvaluation and mispricing, as well as comparisons of traders' final earnings where appropriate.

In the SSW environment, market bubbles and crashes are frequently observed, but there is also considerable heterogeneity between markets. For example, see the left panel of Figure 1, from the data of Cheung et al. (2014); these markets are on average overvalued by eight per cent and mispriced by 32 per cent relative to FV, but there is clearly considerable variation around the mean.

Many studies have examined how market institutions (such as short-selling and futures markets) can improve the performance of SSW markets, and have found the introduction of such institutions to have only limited success (see Palan, 2013, for a review). This motivates a shift toward studies of the psychological and biophysical characteristics and states of market participants, which we review here. However, it has also been claimed (Kirchler et al., 2012) that mispricing in SSW markets may simply be an artifact of the fact that subjects – typically university students motivated by real monetary earnings – are 'confused' by declining FV. This raises two issues, which we address in turn. The first is the role of subjects' beliefs regarding the rationality and behavior of others. The second is the scope for extensions of the SSW design to allow for non-declining FV.

Recall the markets in the left panel of Figure 1, which exhibit substantial mispricing and heterogeneity across markets. As it turns out, all subjects in each of these markets were thoroughly tested on their understanding of declining FV, but this was not made public knowledge (hence the acronym 'NPK' appearing above this panel). Thus, while none of these subjects were themselves 'confused', they may have believed that some others in the market might be confused, and so may have perceived an opportunity for profitable speculation. In the markets whose data are displayed in the right panel of Figure 1, all subjects were similarly tested on their understanding that FV was declining, but this was made public knowledge ('PK') such that subjects in these markets should have no reason to doubt the rationality of others. The resulting markets are on average undervalued by six per cent and mispriced by 20 per cent, with both measures being significantly lower than in the NPK markets (Cheung et al., 2014). Given that many of the studies we review in this chapter manipulate the composition of the market with respect to characteristics such as cognitive ability or gender, this result highlights the importance of whether subjects are aware of such manipulations, as such knowledge may influence their expectations regarding the behavior of others and in turn affect their own actions.

While confusion alone cannot explain mispricing in SSW markets (see also Akiyama et al., 2017), it remains the case that declining FV may not be representative of naturally-occurring markets. There are several ways to induce non-declining FV in SSW style markets. One appealing approach is to introduce interest on cash (in conjunction with a terminal redemption value on shares; for details see, for example, Holt et al., 2017). In this review, we interpret the SSW paradigm broadly to encompass extensions such as this. However, we note that even markets for assets with constant FV are characterized by considerable overvaluation and heterogeneity (Noussair et al., 2001), which again cannot be explained by features of the market environment alone. There is thus considerable scope for psychological and biophysical variables to enter the frame, despite their irrelevance under standard theory.

For our purposes, a key distinction can be drawn between variables that are fixed individual characteristics of market participants, such as gender and cognitive ability, and ones that are transitory states, such as emotions and phases in the circadian cycle. We review these separately in the following sections. In the case of fixed characteristics, a researcher may either measure these variables without making them a target of selection, or purposefully construct markets based upon them (for example, by comparing markets composed of males to ones composed of females). An advantage of the former approach is that it makes it straightforward to examine the effects of multiple characteristics; an advantage of the latter is that it makes it possible to identify causal effects of a single variable of interest. As illustrated by the discussion of Cheung et al. (2014) above, when markets are purposefully constructed it may also matter whether this is known to the participants; in other words, the knowledge of market composition may have important causal effects of its own. In the case of transitory states, a researcher may be able to measure the relevant variables repeatedly or even continuously over the life of the market, as well as to temporarily manipulate the levels of these states.

Fixed characteristics

Personality

Personality is a cornerstone of the psychology of individual differences, so it is perhaps surprising that its relation to economic behavior appears to be weak. Becker et al. (2012) examine associations of the so-called Big Five personality traits with experimental and survey measures of economic preferences. For risk and time preferences – these being the preference dimensions most relevant to financial decision making – the authors find that correlations with personality measures tend to be small, statistically insignificant, and not always consistent across datasets.

In the context of SSW markets, studies of personality have focused on its relation to the individual behavior of traders, and have not used measures of personality as a basis to manipulate the composition of the market. Oehler et al. (2018) find that more extroverted individuals are more prone to make purchases above the prevailing market price, while individuals who are more neurotic hold fewer shares. Cheung and Zhang (in preparation) classify traders' behavior for consistency with fundamental, momentum, and speculative strategies. They find that individuals who are more neurotic are more likely to follow fundamental value strategies and are less likely to be speculators. For the remaining Big Five traits, there are no significant effects.

While this literature finds few notable effects, those that are found are at least broadly compatible: the weight of evidence in Becker et al. (2012) indicates that extroverts tend to be more risk taking, while neurotic individuals take fewer risks. This is consistent with trading on fundamental value being a less risky strategy than speculation, where in the context of an overvalued market a fundamental value trader will also tend to hold fewer shares.

Cognitive ability

The suggestion that mispricing in SSW markets may in part be an artifact of subjects' 'confusion' (Kirchler et al., 2012) highlights the potential importance of cognitive ability in understanding behavior in these experiments. Moreover, since trading in a market involves strategic interaction with other market participants, a trader's beliefs regarding the skill and behavior of others may also come into play, as highlighted by the public knowledge manipulation of Cheung et al. (2014). An emerging literature links cognitive ability to a range of preferences, beliefs, and behaviors that are likely also to be relevant in a financial context. Thus Burks et al. (2009) and Dohmen et al. (2010) find that individuals with higher cognitive ability tend to be less risk averse and more patient, while

Carpenter et al. (2013) and Gill and Prowse (2016) find that such individuals also exhibit greater sophistication in strategic interactions.

Several SSW studies collect measures of cognitive ability – most commonly, the three-item Cognitive Reflection Test (CRT) of Frederick (2005) – and correlate traders' scores with their performance or behavior in the market. These studies typically find that higher-ability subjects also tend to attain larger earnings (e.g., Breaban & Noussair, 2015; Corgnet et al., 2015; Cueva & Rustichini, 2015; Noussair et al., 2016). Breaban and Noussair (2015) also find that higher CRT scores are positively associated with the adoption of fundamental strategies, and negatively associated with momentum strategies. Cheung and Zhang (in preparation) examine multiple dimensions of cognitive ability, and find their relation to trading strategy to be complex and multifaceted. Fundamental strategies are associated with series reasoning (a task that requires identifying the next item in a sequence), speculation with Raven-style matrix reasoning (a task that involves identifying the geometric shape that best completes the stimulus), and momentum trading with verbal reasoning.

Hefti et al. (2016) argue that cognitive ability alone does not suffice to explain trading success, because theory of mind skills (ToM) are also needed to infer the intentions and beliefs of other traders. The authors contend that both types of skill are necessary to trade successfully, and that deficiency in one cannot be compensated for by strength in the other. Hefti et al. (2016) conduct an SSW experiment in which traders' skills on both dimensions are measured (but not used to determine the composition of markets). The correlation between the two skills is found to be low, and traders who are strong in both enjoy the largest earnings. On the other hand, Cheung and Zhang (in preparation) find no significant effects of ToM or its interaction with cognitive ability on trading strategy. One explanation may be that Cheung and Zhang's verbal reasoning measure of cognitive ability partly captures the 'non-analytical' forms of intelligence that others have ascribed to ToM.

At an aggregate level, Breaban and Noussair (2015) and Cueva and Rustichini (2015) find that markets in which the average cognitive ability of traders is higher (through random variation, as opposed to purposeful assignment) tend to exhibit less mispricing. Going beyond correlational analyses of this type, two studies examine the effect of purposefully manipulating the composition of the market, with somewhat conflicting results. Bosch-Rosa et al. (2018) compare markets composed solely of low versus high cognitive ability subjects, finding that high-ability markets exhibit significantly less mispricing (with no significant difference in overvaluation). Hanaki et al. (2017) extend this approach by comparing homogeneous high- and low-ability markets with mixed ones, and systematically examining the effect of subjects' knowledge of the market composition. In contrast to Bosch-Rosa et al. (2018), Hanaki et al. (2017) find no significant difference in mispricing between homogeneous high- and low-ability markets, with both tracking FV similarly well. Instead, they find that mixed markets exhibit significantly greater mispricing than either high- or low-ability markets. Moreover, they find no significant effect of the knowledge of market composition, irrespective of whether that composition is high, low, or mixed.

Thus, to summarize the literature on cognitive ability in SSW markets, the evidence from correlational analyses generally indicates a positive association of cognitive ability with both individual and aggregate outcomes, although Hefti et al. (2016) suggest that cognitive ability alone may not be sufficient. To date, only two studies have examined the causal effect of constructing markets of different ability levels, with mixed results. Further research is needed to replicate and clarify these findings.

Gender

A large body of research examines the possibility of gender differences in behaviors potentially related to financial decision making. Much of this work is reviewed by Niederle (2016). It has been found that women and men perform differently under competitive incentives (Gneezy et al., 2003), and that women are less likely than men to select into competitive environments (Niederle & Vesterlund, 2007). The latter finding has been attributed to a combination of gender differences in confidence, competitiveness, and risk preferences – all of which are relevant in financial settings. Women bid higher than men in first-price auctions (Chen et al., 2013), consistent with women being more risk averse. However, Niederle (2016) cautions that gender differences in risk preference, while likely real, may be smaller and more heterogeneous than widely presumed.

For our purposes, two themes from this broader literature are worth highlighting. First, it has been found that gender differences in behavior vary between single-sex and mixed environments (Booth & Nolen, 2012). Second, while research has begun to investigate the biophysical underpinnings of gender differences in competitiveness and bidding behavior – for example, by examining how the behavior of women varies over the estrus cycle – results to date have been decidedly mixed, with Niederle (2016, p. 492) concluding that 'clearly no obvious consensus has been reached'.

Until recently, gender was not a variable of interest in research on SSW markets – Palan's 2013 review does not cite any papers or results about it. Eckel and Füllbrunn (2015, p. 914) assemble data on 35 markets from six studies in which the proportion of women in the market could be determined. They find this proportion to be significantly negatively correlated with the extent of overvaluation. In our own reanalysis of the same data, we find *no* significant correlation between gender composition and the severity of mispricing (Spearman rho = −0.125, $p = 0.473$). Taken together, these results indicate that prices in markets with more women tend to be lower, but not necessarily closer to the risk-neutral FV.

Four recent studies examine the effects of purposefully manipulating the composition of the market with respect to gender. They differ from each other in whether the gender manipulation is known to subjects, and whether FV follows a declining or constant path (as well as the methods used to induce constant FV). The picture that emerges from these studies is not at all clear. Figure 2 and Table 1 report our own synthesis of this literature.

Eckel and Füllbrunn (2015) compare all-male, all-female, and mixed markets with declining FV. The gender composition was known because subjects could observe who would be in their market prior to the start of the experiment. As seen in the bar chart in the top left of Figure 2, overvaluation declines monotonically comparing male to mixed and female markets, with the male-mixed and male-female differences being statistically significant (Table 1, top panel). However, the line chart shows a non-monotonic pattern for mispricing, which is lowest (with marginal significance) in mixed markets.

Two studies compare all-male and all-female markets with declining FV and *unknown* composition. We pool their data in the top right of Figure 2 and the second panel of Table 1. Eckel and Füllbrunn (2017) are concerned with the extent to which their 2015 result is driven by stereotype-based expectations about the behavior of others, while Holt et al. (2017) are concerned with the robustness of their primary results, which are derived from a constant FV environment. Taken separately, the results of the two studies are contradictory: Eckel and Füllbrunn (2017) find that gender differences in overvaluation disappear when market composition is unknown (from which they conclude that their 2015 result is consistent with the hypothesis of stereotype-based expectations), while Holt et al. (2017) find that gender differences persist (from which they conclude that Eckel and Füllbrunn's 2015 result is driven by declining FV). After pooling the data of both studies (which employ identical parameters), we find the difference in overvaluation between male and female markets is smaller than when market composition is known, but remains marginally significant; there is no significant difference in mispricing between markets of different genders.

Cueva and Rustichini (2015) and Holt et al. (2017) examine gender effects in markets with constant FV and known composition (depicted in the bottom left of Figure 2)[1] or unknown composition (depicted in the bottom right of Figure 2)[2], respectively. However, these authors use different methods to induce constant FV, such that measures of overvaluation and mispricing are an order of

[1] We thank Carlos Cueva for sharing the data of Cueva and Rustichini (2015).

[2] We pool the 15- and 25-period markets of Holt et al. (2017), since both support the same conclusion.

magnitude smaller in the former study. In neither study are differences between male and female markets ever significant. Cueva and Rustichini also consider mixed-gender markets, which are found (as with the declining FV markets of Eckel and Füllbrunn, 2015) to exhibit the least mispricing.

Two conclusions are evident from our review of this literature on gender. First, where effects are found, they largely manifest as differences in overvaluation rather than in mispricing. Markets composed of women generate prices that are lower but not necessarily closer to FV, and are thus on average no more efficient than markets made up of men – if anything, mixed markets may be most efficient. Second, gender effects are more pronounced in a declining FV environment. Critics of that environment may dismiss those results on the basis that declining FV lacks ecological validity and is 'confusing' to subjects. However, another interpretation is that since behavior under declining FV is inherently more variable, it may have greater power to identify factors that explain that variation. To observe gender differences reliably in constant-FV environments may simply require a much larger number of (rather costly) market observations. (See Niederle, 2016, for a related discussion of the role of the elicitation procedure in identifying gender differences in risk preferences.)

Transitory states

Hormones

When we confront risk and reward, our bodies react by modulating the levels of circulating steroids, including sex hormones. Cueva et al. (2015) measure endogenous levels of cortisol and testosterone in an SSW experiment. Sessions were all-male, all-female or mixed, but otherwise not constituted according to baseline hormone levels. Measuring hormone levels at the start and end of each session, they find the market average pre-trading cortisol level is positively associated with mispricing, but for male and mixed markets only. The market average testosterone level, separately averaged by gender, was not significantly associated with mispricing, nor was it correlated with trading profits of males or females.

As their first study could not establish causality, Cueva et al. conducted a second one in which they administered supplemental cortisol or testosterone, but to male subjects only. This second study focused on individual investment behavior and did not involve a market experiment. They found that hormone supplementation led to a decrease in risk aversion, either directly (for cortisol) or by inducing greater optimism regarding future asset prices (for testosterone). They also measured their subjects' 2D:4D ratio but found no evidence that this moderated the response of investment decisions to testosterone administration. This null result is notable given an earlier finding by Coates et al. (2009) that for high-frequency traders there is a significant interaction between the 2D:4D ratio and circulating testosterone levels. Coates et al. found that on high baseline testosterone days (relative to that trader's median), profitability increased, and that this effect interacted with 2D:4D ratio. Neither of these two studies involve an SSW experiment, however.

Nadler et al. (in press) address these contradictory findings with an SSW experiment consisting of 140 male subjects and the double-blind, placebo-controlled, exogenous administration of testosterone. They hypothesize that testosterone administration will shift subjects' thinking toward 'System 1', with optimistic price expectations resulting in raised prices and inflated bubbles. The experiment was repeated several times, with the effects of testosterone administration – higher bids, asks and prices relative to placebo-treated sessions, leading to larger and longer bubbles – being most pronounced in the first market repetition. These results suggest that there is indeed a causal impact of testosterone administration on bubble inflation in men, at least temporarily. Both cortisol and testosterone have an inverted U-shaped dose response curve for performance: too little and we do not trade, too much and irrational exuberance takes hold. Nadler et al. note that some male traders self-administer a testosterone gel before trading, and speculate that this may exacerbate financial market volatility. What effect testosterone gels would have in women, if any, is essentially unknown, and to find out might raise ethical as well as scientific concerns.

Systems 1 and 2

Nave et al. (2017) found that exogenous testosterone administration lowers performance on the Cognitive Reflection Test, suggesting a shift away from System 2 to System 1 reasoning. Some asset market studies focus more directly on the effects of nudging traders toward either System 1 or System 2 thinking. Dickenson et al. (2017) and Kocher et al. (2018) each investigate environments likely to promote System 1 thinking. The former study uses an online experiment to examine whether circadian-mismatched traders in a global market perform worse than traders in local markets composed solely of participants from a single time zone. They hypothesize that sleepy traders will be less able to anticipate others' actions, and so will hold more shares later in the experiment, thereby making less money. They also hypothesize that global markets (with sleepy traders) will produce larger bubbles than local markets. However, they find only modest evidence for greater mispricing and overvaluation in global markets, and no effect on earnings for their cognitively-strained sleepy subjects.

Kocher et al. (2018) compare markets where traders have depleted self-control with ones comprised of non-depleted traders. The experiment follows a 'Stroop' task (Stroop, 1935) in which participants are presented with a series of word-color combinations and asked to identify the color of the font in which the word (itself the name of either the same or a different color) is displayed. In the difficult (self-control depleting) version of this task the name and color are always in conflict, whereas in the placebo version such conflict almost never occurs. Kocher et al. suspect that a lack of self-control contributes to more impulsive bidding. They find large effects of self-control depletion in the form of more aggressive bidding and greater overvaluation, and a particularly pronounced effect upon mispricing. Since they also find that depleted traders experience stronger self-rated emotions, they suggest that depletion exerts its influence by enhancing traders' sensitivity to these emotions. A second experiment with mixed markets comprised of both depleted and non-depleted traders does not find any effect on traders' profits, corroborating the unexpected null result in Dickenson et al. (2017) for the profits of sleepy traders who presumably rely more on System 1 reasoning.

Two further studies take the opposite approach, aiming to enhance System 2 thinking to see whether doing so improves market outcomes. Ferri et al. (2016) mandate time for deliberation and reflection in an SSW experiment, using a ten-second 'cooling off' period for each trade, compared with a no-time-delay treatment. They find that the time delay greatly reduces volatility and price dispersion. However, markets are undervalued in both treatments, and more so for time-delay markets, leading to worse mispricing in the delay treatment, assuming that traders are risk neutral. The authors then re-estimate FV using the measured risk aversion of their subjects, and find that the time-delay treatment tracks this risk-averse FV closely throughout the experiment. Finally, Cheung and Palan (2012) compare markets in which each decision making unit is a team of two, who must agree on each transaction they make, to conventional markets populated by individuals. They find that the teams treatment reduces bubbles, presumably because teams must deliberate to justify and agree on their decisions.

Taken together, these studies provide evidence that the decisions of traders relying on System 1 thinking, whether through sleepiness, high testosterone or impulsivity, lead to greater market volatility than the decisions of traders relying more on System 2 thinking.

Emotions: Induced through priming

Background emotional states can influence our attitudes to risk and reward by changing the neuronal firing threshold in our brains (Kennedy, 2011), which may affect trading decisions. Several studies investigate how asset markets behave when traders in some markets are emotionally primed prior to the start of trade. Andrade et al. (2016) use video clips to induce excitement, fear or calm, prior to an SSW experiment. All subjects in each market watch the same video; the authors do not consider mixed markets. Psychologists use the term 'valence' (which may be positive or negative) to describe the intrinsic attractiveness or aversiveness of an emotion, and 'arousal' (which may be high or low) to describe its intensity. Andrade et al. find that clips featuring high arousal and positive valence (intended to induce excitement) lead to significantly greater overvaluation than clips invoking high-arousal negative valence (fear) or low-arousal positive valence (calm). Other effects were marginal or insignificant. They argue that excitement has the strongest effect due to the congruence between contextual cues from a rising market and the stimulus, whereas the clip inducing fear has less effect as it lacks congruence with the context, such that the fear state is incidental and not reinforced. They do not proceed to investigate whether induced fear would enhance or dampen the downturn in crash-prone markets.

Newell and Page (2017) examine whether priming in boom or bust conditions (using a procedure developed by Cohn et al., 2015) affects subsequent trading behavior in an SSW experiment. Each market is comprised of traders who experience the same priming, in the form of a fictitious market price chart showing trajectories for strong gains (the 'boom' condition) or strong losses (the 'bust' condition). Subjects are then asked a series of questions designed to engage them with the economic realities of the scenario they are presented with, and thereby put them in the desired disposition. No control treatment is included for comparison.

The authors hypothesize that when traders are primed for boom conditions, bubbles will be larger, mispricing greater and price forecasts less accurate. They find overvaluation in both treatments, but significantly more so in the boom treatment. They also find less risk aversion, worse price predictions, and slightly greater mispricing in the boom condition. Newell and Page interpret their results in terms of countercyclical risk aversion, whereby self-reinforcing feedback loops exacerbate initial market movements away from FV. As they note, their results are consistent with those of Andrade et al. (2016) in that excitement is associated with boom times and fear is associated with busts.

Emotions: Repeated measures

We previously noted evidence for strong coherence between different measures of fluctuating emotions (Levenson, 2014; Mauss et al., 2005), such as self-reports, skin conductance and facial expressions. Hargreaves-Heap and Zizzo (2011) elicit self-reported emotions during an SSW experiment, while Breaban and Noussair (2018) employ face-reading technology to assign emotional states to changes in facial expressions during trading. The former study uses a seven-point Likert scale to measure subjects' feelings of anger, anxiety, excitement and joy. They find little effect of anger or joy, but significant and opposing effects of excitement and anxiety, the latter likely being a proxy for fear. Excitement is associated with overvaluation, and anxiety with trading close to FV. Emotional state is not related to traders' profits. The authors find evidence that a momentum effect arises endogenously via the effect of earlier price changes on excitement, raising current prices and creating a self-reinforcing feedback loop away from FV.

Breaban and Noussair (2018) are also interested in the effect of emotional changes during trading in SSW markets. They use a novel face-reading software called Noldus Facereader to identify the 'universal' expressions associated with happiness, surprise, anger, disgust, sadness, fear, 'neutrality' and overall emotional valence (defined by Breaban and Noussair as 'a composite measure of the positivity of emotional state'). The more highly cognitively-mediated emotions such as regret, which we assume to be specifically human, are not associated with a facial expression by Noldus Facereader. Breaban and Noussair (2018) find that the initial market average level of overall valence correlates positively with overvaluation, while initial fear (which is negative in valence) correlates with price decreases and selling. They find that the other emotions correlate with higher prices when positive, and lower prices when negative, but none are statistically significant. In general, the levels of different emotions can predict the direction but not the extent of price changes.

Breaban and Noussair (2018) also find that sales rise with *contemporaneous* fear, while purchases rise with *lagged* overall valence. They then assign each trader to one of three types: fundamental traders and speculators, both of whom are rational, and momentum traders, who are not, based on their buying and selling decisions while trading. Their strongest findings apply to momentum traders (34 per cent of the sample), who buy more when market average valence is positive and sell more when it is negative. On average, these momentum traders earn less money than the other types. They also find that fear, anger and surprise increase as a crash unfolds, but that just after the crash, surprise (which is neutral in valence) falls away and sadness (which is negative) rises instead. Finally, they find that traders who can maintain a relatively neutral emotional state during a crash earn greater profits overall, indicating that emotional self-regulation is important for trading success.

fMRI

Several studies use fMRI to measure neural activity during an SSW experiment. This records the uptake of glucose in different brain regions known to be involved in specific neural processes, in the form of blood oxygenation level dependent (BOLD) signals, in near real time. The main limitations are small sample sizes, due to cost, and the need for a subject to lie in a scanner during the decision process, which restricts the kinds of tasks that can be measured.

De Martino et al. (2013) compare fMRI BOLD signals in bubble markets with those in non-bubble markets for subjects with varying theory of mind (ToM) abilities. They find that high ToM can be maladaptive when interacting with modern financial markets, even though the ability to infer the intentions of others is usually advantageous. A possible explanation is the interaction between cognitive ability and ToM as proposed by Hefti et al. (2016), discussed above, who argue that the most successful traders need both capabilities to judge the market correctly. Specifically, Hefti et al. find that 'semiotic' traders, who have ToM above the median but cognitive ability below the median, perform poorly. These traders assign intentionality to the market itself and ride the bubble to its peak, but fail to sell out in time. De Martino et al. (2013) find greater activity in the ventromedial prefrontal cortex for those with a tendency to ride the bubble, interacting with stronger signals in the dorsomedial prefrontal cortex (a proxy for gauging intentionality), but only in sessions in which bubbles were present.

Smith et al. (2014) use fMRI to identify differential BOLD signals for those who ride the bubble up and sell out in time, compared with those who continue to buy or hold shares beyond the market peak. They find that in aggregate, neural activity in the nucleus accumbens (NAcc) tracks the expansion of the price bubble and can be used to predict future price trends. They also find that those traders who ride the bubble up but then fail to time their exit have particularly strong NAcc activity, which the authors interpret as a reinforcement and reward for buying. We noted earlier that testosterone affects dopamine transmission in the NAcc, but that this signal exerts its influence subconsciously. Smith et al. find that those who make the most money also exhibit a second BOLD signal, in their right anterior insula, that just precedes the peak of the bubble. The authors interpret this signal as an early warning indicator, perhaps reflecting discomforting somatic markers, which acts as the trigger to sell out to the bubble riders who do not experience this signal. The selling activity of those who experience this signal then precipitates the bursting of the bubble. The anterior insula is known to be associated with the processing of interoceptive signals, the experience of pain, and other emotional processing.

Discussion and conclusion

Implications for research

We have focused in this chapter on psychological and biophysical measures used in laboratory asset markets. We should be mindful of the limitations of such experiments, which include: greatly simplified environments; convenience samples of students (inexperienced and not representative of real-world traders); comparatively low-powered incentives that may not sufficiently engage the biophysical underpinnings of emotions; small numbers of participants within each market; and comparatively small samples of market observations (typically fewer than ten observations per treatment condition). In their favor, we note that while not highly representative of professional traders, students may be more representative of retail investors making financial decisions, from those juggling retirement portfolios to those following the latest cryptocurrency craze. There is also a potential tradeoff between the external validity of experimental results and our ability to make causal inferences. In general, laboratory experiments emphasize the latter over the former. Given the limitations afflicting the experimental study of markets, one logical direction for future research is to bring psychometric and biophysical measurement into naturally occurring financial markets. We have referred above to some examples of this type of research.

We further caution that the effects of many variables are not always as clear cut – nor as eye catching – as a superficial reading of the most high-profile studies alone might suggest. For example, we have seen how the effects of variables such as cognitive ability and gender are complex and subtle, varying with factors such as the FV structure, knowledge of market composition, and the distinction between overvaluation and mispricing. Such nuances may be too arcane for non-specialists, and are easily glossed over in an emerging field seeking to make a name for itself through headline-grabbing results. It is more reassuring to be able to fall back on simple certitudes such as 'smart people are more rational', or that 'women are less aggressive'. Further, again taking cognitive ability and gender as examples, we have seen instances where near-contemporaneous studies, with very similar designs and research questions, have yielded nearly diametrically-opposing results. Though not as professionally rewarding to researchers, we emphasize that null results, as well as efforts at replication, are essential for scientific progress in a relatively youthful field such as this. Of course, the above observations hold with equal force for studies of biophysical measurements and manipulations, such as fMRI or testosterone administration.

Implications for our understanding of markets

Keynes (1936) referred to our 'animal spirits' as a source of instability in financial markets and, more recently, Shiller (2000) refers to our tendency towards 'irrational exuberance'. On the other hand, Damasio (1994) has shown how access to our somatic reactions to risk and reward is essential for advantageous decisions. Optimal risky choices are impossible without somatic signals, but those same signals can also goad us to swing too far into optimism and pessimism (Coates & Page, 2016). So, are the emotions we experience at the time of decision essential, or at least helpful? Or are they disruptive to decision quality? If the latter, how can these emotions have remained so tightly interwoven with our choices over evolutionary time if they are not, on balance, advantageous to decision making?

The literature typically draws a distinction between emotions that are 'integral', and so advantageous for decisions, and ones that are 'incidental', and typically detrimental to decision making (Bechara & Damasio, 2005; Fenton O'Creevy et al, 2012). While sensible as far as it goes, this distinction does not sufficiently capture the fine line between harnessing one's integral emotions and being a captive to them. Like fire, our emotions can be both a powerful servant to achieve our goals, and a dangerous master that can undermine them. Evidence suggests that emotional self-regulation can make a critical difference to which of these outcomes occurs (Fenton O'Creevy et al, 2012, and references therein).

Further evidence suggests that emotional self-regulation manifests biophysically in our vagal tone. Experienced traders claim that emotional self-regulation when trading in volatile markets is a core skill they need to acquire: 'for traders, low HF HRV is associated with greater susceptibility to incidental emotions and greater difficulty using integral emotions as a guide' (Fenton-O'Creevy et al., 2012). Indeed, Bechara and Damasio (2005) observe that lesion patients perform *better* than normal subjects do when the latter are suffering a wave of anxiety or fall in confidence. The lesion patient's decisions are not susceptible to somatic signals, whether helpful or disruptive alike, and so avoid the despair that can spread through markets.

Implications for market design, regulation and policy

Human traders, in particular the young males who dominate the world's trading floors, face a maelstrom of emotions when facing risk and reward; not every trader is a very stable genius. We noted earlier that cortisol and testosterone have an inverted U-shaped dose response curve for performance. Financial markets must thus navigate a tightrope of instability, seeking to avoid waves of optimism and pessimism that threaten to sweep away these young males with consequences for us all. To limit the damage caused by market instability, can we engineer the choice architecture of financial markets to be safer for human traders, as we design cars with myriad safety features to be robust to human drivers?

Coates et al. (2010, p. 340) and Eckel and Füllbrunn (2015, p. 919) both suggest that financial markets would be less volatile if they were more gender-balanced, raising obvious questions of how this might be achieved, and whether policy interventions are either necessary or appropriate. At the same time, and perhaps to contrary effect, there is growing anecdotal evidence that some financial professionals undergo pharmacological enhancement, for example by taking testosterone supplements in the belief that this will make them more competitive in the workplace (Wallace, 2012), or antidepressants that modulate serotonin pathways. The consequences of these (largely unregulated) actions for traders' performance, and for market stability more broadly, are to date for the most part unexplored.

Under the EMH, algorithmic trading can help to eliminate arbitrage opportunities and bring about greater stability and efficiency. Alternatively, since algorithms are created by humans, they may instead amplify human foibles and exacerbate market instability – as seen in so-called 'flash crashes', where markets experience a rapid, but short-lived, plunge in prices. While not directly triggered by algorithms – in some cases, the root cause may be as simple as a 'fat-fingered' human error – the amplitude and speed of these price swings may be exacerbated by the cascade of algorithmic orders they precipitate (Kirilenko et al., 2017). Moreover, as Farjam and Kirchkamp (2018) demonstrate, the expectations and behavior of human traders may in turn be affected in unexpected ways by the knowledge that they may be interacting with algorithms.

If emotional and biophysical responses are essential for humans to make sound financial decisions, how do we incorporate such feedback into our computer algorithms? Alternatively, will the content of these algorithms render moot an inability to do so? We hope that this chapter will stimulate new approaches to these fundamental, and fundamentally human, questions.

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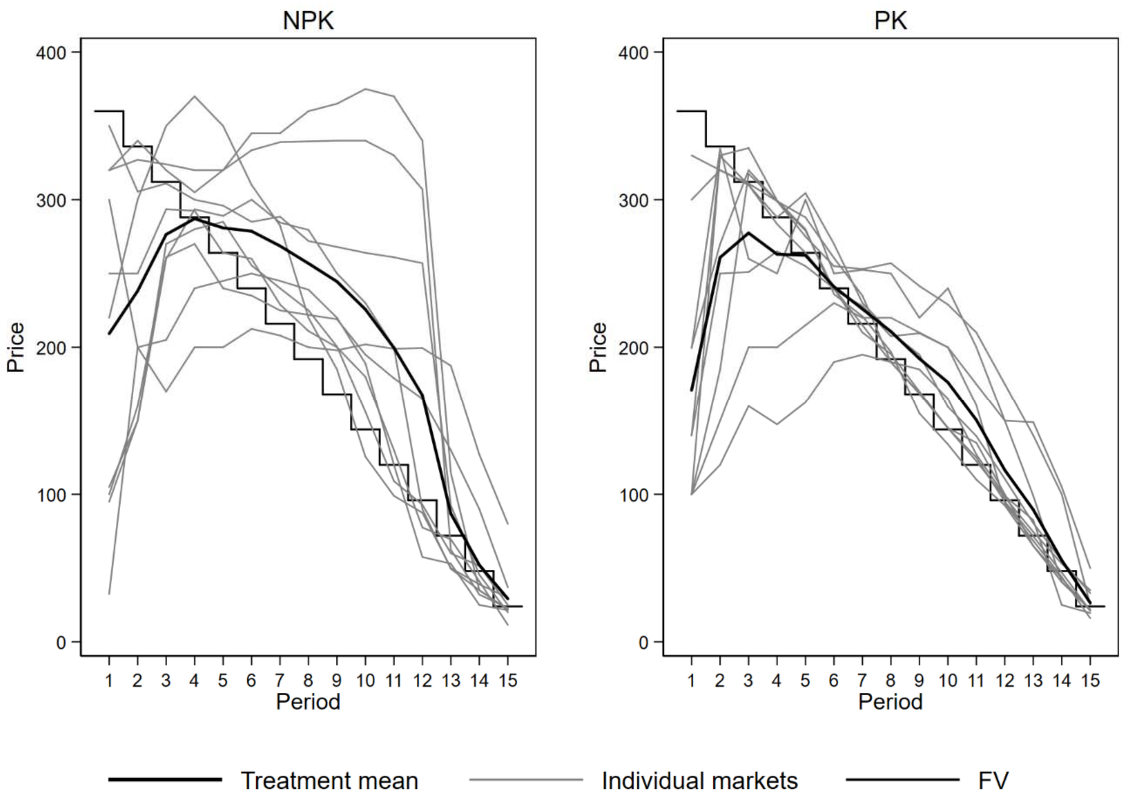
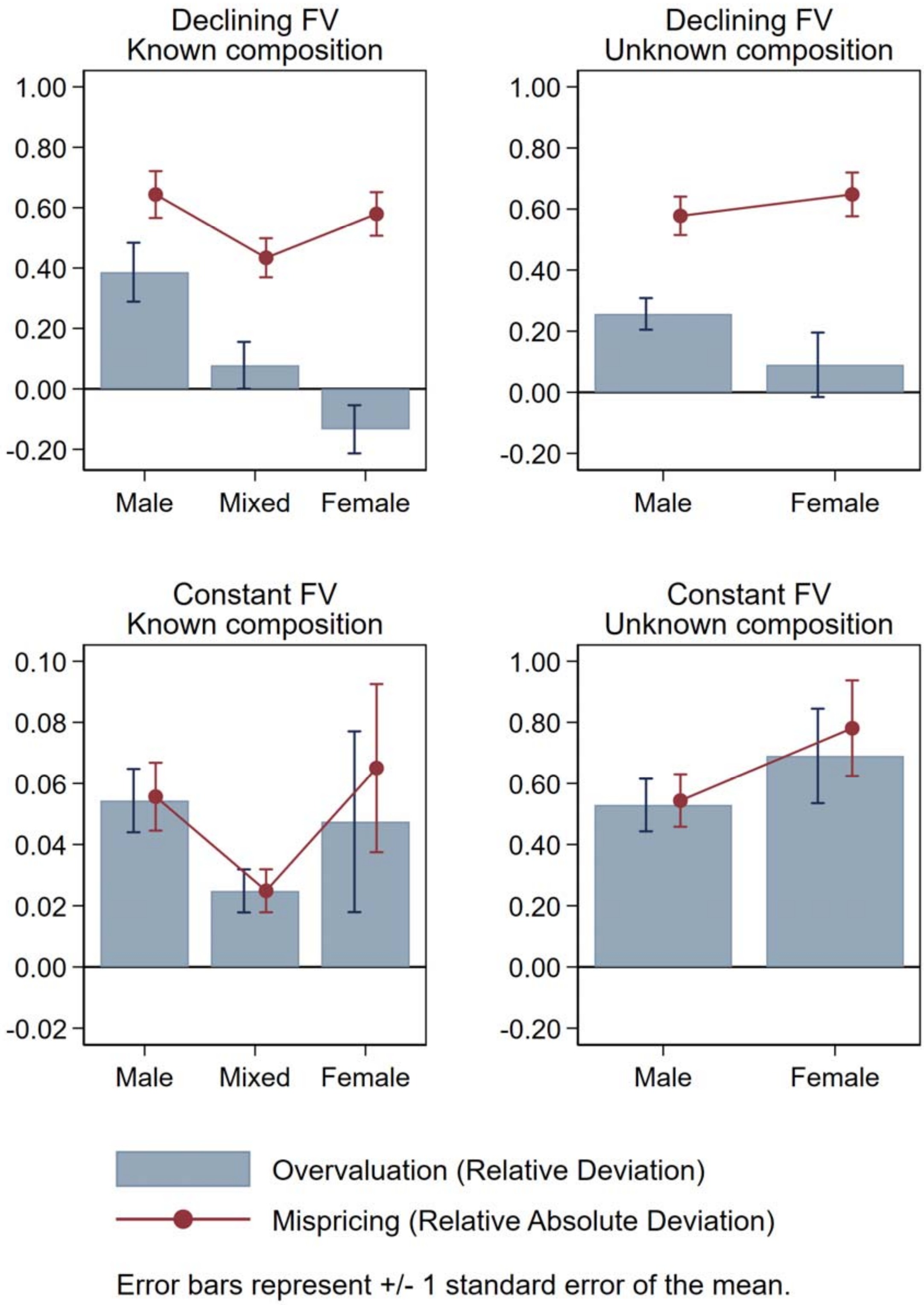
FIGURE 1. Sample price paths in SSW markets, illustrating effect of knowledge of market composition.



Source: Cheung et al. (2014).

FIGURE 2. Effects of gender composition on overvaluation and mispricing.



Source: Authors' calculations, using data of studies cited in the text.

TABLE 1. Tests of gender effects of market composition (Mann-Whitney *p*-values, two-sided).

Condition	Overvaluation (Relative Deviation)	Mispricing (Relative Absolute Deviation)
Declining value, Known composition		
Male versus Female	0.006 ***	0.522
Mixed versus Male	0.032 **	0.063 *
Mixed versus Female	0.116	0.199
Mixed versus Homogeneous	0.735	0.063 *
Declining value, Unknown composition		
Male versus Female	0.095 *	0.469
Constant value, Known composition		
Male versus Female	0.174	0.597
Mixed versus Male	0.059 *	0.059 *
Mixed versus Female	0.821	0.174
Mixed versus Homogeneous	0.218	0.059 *
Constant value, Unknown composition		
Male versus Female	0.608	0.281

* $p < 0.10$; ** $p < 0.05$, *** $p < 0.01$.

Source: Authors' calculations, using data of studies cited in the text.