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Using Non-Invasive Brain Stimulation to Test the Role of Self-Control in Investor Behavior

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Abstract

We test whether self-control causally affects investor behavior with the non-invasive brain stimulation. Subjects trade stocks in an experimental asset market while their levels of self-control are exogenously varied by applying weak currents stimulation to a control-related brain area. We document that modulation of regional cortical excitability related to self-control significantly influences the propensity of realizing capital gains as well as capital losses. Our finding provides support for the role of self-control in the disposition effect and highlights the utility of using non-invasive brain stimulation to causally test the underlying mechanism of investor behavior.

Keywords: self-control; investor behavior; disposition effect; non-invasive brain stimulation

JEL Codes: G02, G11
1. Introduction

In the past several years, the understanding of the neuroscience underlying financial decisions has rapidly advanced (for reviews, see Frydman and Camerer, 2016; Bossaerts and Murawski, 2015), raising hopes that the measurements of neural activity can be applied to behavioral finance research. Two promising avenues for such a contribution have been previously identified. First, neural data, collected by functional magnetic resonance imaging (fMRI), might test the theories of investor behavior (e.g., Frydman et al., 2014; Frydman and Camerer, 2016) and improve the understanding of neural mechanisms for financial decisions (e.g., Bruguier, Quartz and Bossaerts, 2010; De Martino et al., 2013). Second, electrophysiological signals, measured with event-related potentials (ERPs), might provide insights into the processes of financial decisions and predict investor behavior (e.g., Vieito, Da Rocha and Rocha, 2015).1

In this paper, we propose another type of avenue, namely, the modulation of regional neural excitability by means of weak currents with non-invasive brain stimulation while subjects trade in an experimental asset market, can be useful in causally testing the underlying mechanism of investor behavior. To demonstrate this, we use Transcranial Direct Current Stimulation (tDCS) to test for the causal effect of self-control on investor behavior.

Self-control is considered prominent in the early empirical work on financial decisions (Ameriks, Caplin and Leahy, 2003; Biais et al., 2005) and has received attention in recent experimental studies (Kaur, Kremer and Mullainathan, 2015; Kocher, Lucks and Schindler, 2016). The extant literature has considered the effect of self-control on decision making mainly using two sets of methods: self-reported survey-base measures of self-control (Ameriks et al., 2007; Schmeichel and Zell, 2007) and experiments manipulating self-control (Baumeister et al., 1998). However, the use of questionnaires in hypothetical choice scenarios for measures of self-control may result in biased and inaccurate results (Camerer and Mobbs, 2017). Further,

1 For detailed discussion of using neuroscientific tools (e.g., fMRI and ERPs) to make economic predictions, see Camerer (2007).
experiments that manipulate self-control, which draw on the concept of self-control depletion or exhaustion, have also been cast in doubt by meta-analytic tests, which conclude that the resource depletion effect was overestimated (Carter et al., 2015; Inzlicht, Schmeichel and Macrae, 2014). Therefore, although the idea that better self-control can contribute to investor success is evident from the statements of well-known investors, the effect of self-control on investor behavior has not been well documented perhaps because of the difficulty in obtaining ideal data that measure self-control and trading decisions.

Our main contribution is to provide a novel method of modulating self-control, which has been considered relevant for investor behavior, including the well-known disposition effect. The disposition effect is a robust fact indicating that individual investors tend to sell winner stocks too early and hold loser stocks too long (Shefrin and Statman, 1985). Disposition effect entails investment biases that reduce investors’ portfolio returns (Odean, 1998). Despite the near-ubiquity of the disposition effect, its underlying mechanism is not yet fully clear. Many competing alternative theories have been developed to explain the disposition effect. Among them, self-control theory is based on the dual-self model that describes the intrapersonal conflict.

2 Inzlicht, Schmeichel, and Macrae (2014) propose three problems about the resource concept in explaining self-control. First, most experiments do not observe resource depletion directly and just infer its presence or absence based on patterns of performance on the second of two self-control tasks. Second, some findings are inconsistent with the limited resource hypothesis, which suggests that activities such as smoking cigarettes or watching a favorite television program can defend against the reductions in self-control observed in the sequential task paradigm. Finally, the limited resource concept may be functionally implausible. There are real advantages to a system that can put a brake on exploitation in favor of exploration; however, it would make little sense for such a brake to be based on resource limits.

3 For instance, Warren Buffet emphasizes that “success in investing doesn’t correlate with I.Q. once you’re above the level of 25. Once you have ordinary intelligence, what you need is the temperament to control the urges that get other people into trouble in investing.” http://www.businessweek.com/1999/99_27/b3636006.htm

4 Several experimental and empirical studies have documented the disposition effect for individual investors in several countries (e.g., Grinblatt and Keloharju, 2001; Feng and Seasholes, 2005), for different types of assets (e.g., Genesove and Mayer, 2001; Hartzmark and Solomon, 2012), and for several groups of professional investors (e.g., Shapira and Venezia, 2001; Frazzini, 2006).

5 These theories at least include prospect theory (Odean, 1998; Weber and Camerer, 1998), realization utility theory (Barberis and Xiong, 2012; Ingersoll and Jin, 2013; Frydman et al., 2014), regret theory (Summers and Duxbury, 2012), mental accounting theory (Frydman, Hartzmark and Solomon, 2018), peer effect theory (Heimer, 2016; Goulart et al., 2015), cognitive dissonance theory (Chang, Solomon and Westerfield, 2016), as well as belief in mean reversion (Brooks, Capra and Berns, 2012).
between a rational long-run self and an impulsive short-run self (Thaler and Shefrin, 1981; Fudenberg and Levine, 2006). For instance, if an investor encounters capital gain, the myopic short-run self wants to hasten the experience of positive utility (Barberis and Xiong, 2012; Frydman et al., 2014). By contrast, if he suffers capital loss, the short-run self tends to hold it to avoid admitting investment mistakes (Chang, Solomon and Westerfield, 2016). Thus, the short-run self is impulsive to sell the winner stocks and is urged to hold the loser stocks. However, the rational long-run self, who considers maximizing investment profits, can choose a self-control behavior at some reduction in the short-term utility. Given lack of sufficient self-control by the long-run self on the impulsive behavior, an investor will exhibit a disposition effect.

This explanation appears in the first paper on the disposition effect (Shefrin and Statman, 1985), but it has since received little attention or empirical support. As mentioned, when using the method of self-reported survey or experiment manipulation, obtaining ideal data to test the effect of self-control on disposition effect is difficult. However, as we show in this paper, the combination of tDCS and experimental design does allow for direct tests of whether exogenously varying self-control with non-invasive brain stimulation causally affects the disposition effect.

Specifically, we adapt the experimental asset market introduced by Frydman et al. (2014). In the fMRI study of Frydman et al. (2014), they temporally separate the event where a subject receives information about a stock price change from the event where a subject is asked to make a trading decision, enabling them to identify the neural activity generated in response to news about a stock price change. However, with the temporal separation, the behavioral study of Frydman and Rangel (2014) affirms that price information for one stock does not affect the subjects’ trading decisions for another one, and no evidence exists for the cross-stock effects. Additionally, in the individual investor stock account level, the stock price update and trading screen are commonly displayed together. Thus, we combine the price update and the trading

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6 The salience of stock price information affects the disposition effect (Frydman and Rangel, 2014; Frydman and Wang, 2017).
screen. Importantly, to measure the subjects’ self-control, we follow Ameriks et al. (2007) and define a variable called actual-ideal consistent decision, which is measured by whether the actual capital gains (or losses) are consistent with the ideally prespecified capital gains limit (or losses limit). The prespecified capital gain limit (or losses limit) is collected by asking the subjects to report their ideal capital gains and capital losses limit at the beginning of the experiment.

While the subjects perform the experiment, we apply anodal, sham, or cathodal stimulations over the right ventrolateral prefrontal cortex (rVLPFC), the neural region commonly recruited across the different forms of self-control (for reviews, see Cohen, Berkman and Lieberman, 2013; Cohen and Lieberman, 2010; Heatherton and Wagner, 2011). Anodal stimulation is typically associated with increased cortical excitability. By contrast, cathodal stimulation is usually linked with decreased cortical excitability. Finally, sham stimulation just mimics the peripheral effects and does not affect any neural processing.

Our chief hypothesis is that tDCS over right rVLPFC influences the strength of self-control exerted on impulsive behavior and this scenario, in turn, affects the propensity of realizing capital gains and capital losses. Our results show that cathodal stimulation over rVLPFC significantly reduces the disposition effect by decreasing the proportion of gains realized (PGR) and increasing the proportion of losses realized (PLR). Crucially, the underlying mechanism for the cathodal stimulation effect is exhibiting sufficient self-control, which is represented by a high percentage of actual-ideal consistent decisions. These findings advance our understanding of the self-control effects on investor behavior and can inform strategies to potentially improve stock trading decisions.

Our study contributes to the literature that explores the effect of neural or biological factors on financial decision making in a controlled experiment environment. For instance, Frydman et al. (2014) provided neural evidence using fMRI to test the realization utility model for the disposition effect. They find strong

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7 Another popular experiment design used to study disposition effect is Weber and Camerer (1998). The price update and trading in this experiment design are also shown in the same screen.
evidence that investors who realize capital gains experience a positive burst of utility but do not find a negative burst when realizing capital losses. Frydman and Camerer (2016) employed fMRI to test the role of regret in repurchase behavior and showed that the strength of the repurchase effect is correlated with the size of the neural regret signal, which is encoded in the brain when subjects observe an increase in price for previously sold stock. Nadler et al. (2017) tested how testosterone affects stock trading and prices and validated that exogenously elevating testosterone in male traders increases bid prices and stock price bubbles.

Our paper contributes to such literatures by showing that a combination of tDCS, a method of non-invasive brain stimulation, and experimental asset market can be used to causally test the underlying mechanisms of investor behavior. We document that cathodal simulation over rVLPFC significantly reduces the disposition effect by increasing self-control. This finding is important because it demonstrates, for the first time, that self-control causally affects the disposition effect. Regarding recent discussion about whether disposition effect is driven by preferences or beliefs (Ben-David and Hirshleifer, 2012), we argue that preference may be a more convincing explanation because cathodal simulation moderates the propensity to realize capital gains, attenuating the preference of realizing utility (Barberis and Xiong, 2012; Frydman et al., 2014).

2. Related Literature and Theory Background

The present paper relates to the two aspects of behavioral finance and neuroscience literature: disposition effect and self-control. We first review behavioral finance studies on the disposition effect in Section 2.1, and then we discuss the neural mechanism of self-control in Section 2.2.

2.1 Disposition Effect and Self-Control

Shefrin and Statman (1985) verified that individual investors tend to sell winner stocks that are trading above the purchase price and are reluctant to sell loser stocks. They propose some potential explanations for the disposition effect, such as prospect theory, regret theory, mental accounting, and self-control.

A standard explanation of the disposition effect is prospect theory (Odean, 1998;
Weber and Camerer, 1998), a prominent theory of decision-making under risk and uncertainty (Kahneman and Tversky, 1979). According to the S-shaped value function, which is concave in the gain domain and convex in the loss domain, investors will hold the stock that has gone down in value as they are risk-seeking over losses and sell the stock that has risen in value as they are risk-averse over gains. However, Barberis and Xiong (2009) developed a model to test whether prospect theory preferences can predict disposition effect. They conclude that the annual gain or loss model often exhibits the opposite of the disposition effect and that the realized gain or loss model predicts a disposition effect more reliably. Meng and Weng (2017) showed that the prediction of prospect theory depends on the investor reference point. When initial wealth is used as the reference point, there is no disposition effect; but when lagged expected final wealth is employed as the reference point, prospect theory can predict the disposition effect. Kaustia (2010) documented that the propensity to sell jumps at zero return but it is remarkably insensitive to return over wide ranges of losses and is increasing or constant in the domain of gains. This pattern of return realization is inconsistent with the prediction of the S-shaped value function.8

Some strands of literature posit that disposition effect results from regret. Regret is a negative emotional experience when realizing or imagining that our present situation would have fared well (what might have been), had we decided differently (Loomes and Sugden, 1982). When suffering capital losses, investors think that the stock is only a paper loss when they continue to hold it. This way, the feeling of regret could be avoided. By contrast, investors would experience regret after realizing the capital losses. Selling a winner stock induces rejoice, whereas selling a loser stock generates regret. The quest for rejoicing and the avoidance of regret may lead to a disposition to realize gains and defer losses. Lehenkari (2012) provided empirical evidence that the disposition effect is more pronounced for self-purchased stocks than for inherited or gifted stocks and confirmed that regret drives the disposition effect. Summers and Duxbury (2012) experimentally demonstrated the effect of regret on the

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8 For other evidence that show prospect theory cannot fully explain the disposition effect, see Hens and Vlcek (2011), Lehenkari (2012), and Summers and Duxbury (2012).
disposition effect.

Mental accounting is also a potential explanation for the disposition effect. When a stock is purchased, a mental accounting is opened (Thaler, 1985). An investor would track the gains or losses accrued on the stock and is reluctant to close a mental accounting at a loss, which involves admitting to having made an investment mistake. Frydman, Hartzmark, and Solomon (2018) showed that, when investors sell a stock and quickly buy a different stock, the mental accounting used to track the sold stock is not closed and would be rolled into the new stock. They find that rolling a mental accounting alleviates the pain of realizing a loss, and thus reduces the disposition effect.

Another explanation of the disposition effect, and the one we focus on in this paper, is self-control, which is based on the dual-self hypothesis (Shefrin and Statman, 1985). To adapt the dual-self model for an analysis of the disposition effect, we argue that the short-run myopic self has “baseline preferences”, which depends only on the current investment outcome. The short-run self is impulsive or tempted to hasten the experience of positive utility by selling winner stocks and is urged to avoid admitting investment mistakes by holding loser stocks (Barberis and Xiong, 2012). Conversely, the long-run self considers future investment performance and chooses a self-control behavior that influences the utility of the short-run self. That is, at some reduction in utility (for both selves) the long-run self can choose preferences other than the baseline preferences (Fudenberg and Levine, 2006). The long-run self is faced with the choice of which preferences to give the short-run self, or equivalently, how much self-control to exert. It is the myopic short-run self that pursues the baseline preferences, and the long-run self may not exert enough self-control to prevent the impulsive behavior of the short-run self from interfering with rational decision

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9 Barberis and Xiong (2012) suggest that investors derive utility from realizing gains/losses of stocks they own and present a model of “realization utility”. Heimer (2016) empirically find that social interaction can contribute to some traders’ disposition effect, and financial peer effects asymmetrically relate to gains and losses. Furthermore, the controlled laboratory experiments of Goulart et al. (2015) shows that a significant increase in the disposition effect occurs when the subjects’ stock trading performance is to be made public, and this increase essentially results from a spike in the realization of gains.
making, thereby resulting in the disposition effect. Shefrin and Statman (1985) proposed that investors may be clearly aware that holding loser stocks and selling winner stocks are not rational, but their problem is to exhibit sufficient self-control to realize capital losses and hold winner stocks.

The self-control problem may be addressed with various pre-commitment devices, such as stop-loss and take-gain orders. The stop-loss and take-gain orders can automate an exit device, reducing reliance on an investor’s impulse control. The value of automatic selling devices may be as a self-control mechanism that allows investors to manage their reluctance to realize losses and eagerness to realize gains. Using a panel survival approach on data from an internet trading platform for currencies, Nolte (2012) confirmed that the use of stop-loss and take-gain orders can reduce the disposition effect.10 Fischbacher, Hoffmann, and Schudy (2017) further provided experimental evidence that automatic selling devices reduce the disposition effect by helping investors realize loser stocks whereas reminders about pre-specified selling plans are not enough to reduce the disposition effect. Therefore, self-control is one of the plausible candidates to explain the disposition effect, it has not yet been directly tested.

2.2 Neural Basis of Self-Control

Self-control is a broad concept that has been defined in different ways. A general definition of self-control is “the overriding or inhibiting of automatic, habitual, or innate behaviors, urges, emotions, or desires that would otherwise interfere with goal directed behavior” (Muraven, Shmueli and Burkley, 2006). When people exert self-control, they inhibit their emotional, impulsive, or automatic behavior. People exert self-control because they want to follow their goal-directed behavior (either intentional or incidental). A common structure of self-control, by definition, entails an ideal action that people would like to take and something (e.g., addiction, temptation, or emotion) that interferes with this ideal. The actual behavior is a tradeoff among

10 Richards et al. (2017) demonstrates that use of ordinary stop-loss and trailing stop loss orders is an effective tool to decrease the UK investors’ disposition effect. Linnainmaa (2010) finds that Finnish investors who use take-gain orders have a higher disposition effect.
these forces (Ameriks et al., 2007).\textsuperscript{11}

Previous fMRI studies have suggested that the right ventrolateral prefrontal cortex (rVLPFC) is a common neural basis of exerting self-control in a variety of domains (Cohen, Berkman and Lieberman, 2013; Cohen and Lieberman, 2010).\textsuperscript{12} McClure et al. (2004) tested the neural correlates of time discounting and demonstrated that two dissociable neural systems are involved while subjects choose between an immediate monetary reward and a delayed monetary reward. They find parts of the limbic system associated with the midbrain dopamine system are activated by decisions involving immediate available rewards. In contrast, rVLPFC is one of the key regions for successfully choosing the delayed monetary reward. Wager et al. (2008) examined the relationship between the rVLPFC and emotion regulation.\textsuperscript{13} In their experiment, subjects view images that are neutral or that elicit negative emotions and are asked to use a technique called cognitive reappraisal to decrease the intensity of the emotion felt toward the negative images. They find that rVLPFC activity is correlated with reduced negative emotional experience during cognitive reappraisal, indicating that this region is involved in the control of emotions. Other fMRI studies indicate that the right inferior frontal gyrus, a region within the larger rVLPFC, plays an important role in exerting control over cognitive dissonance (Jarcho, Berkman and Lieberman, 2011) and over risky behavior (Christopoulos et al., 2009).

Moreover, it is important to note that other prefrontal areas, such as the dorsolateral prefrontal cortex, medial prefrontal cortex, and anterior cingulate cortex, are involved in tasks that require self-control. However, Cohen, Berkman, and

\textsuperscript{11} Models that fit this general framework include the model of quasi-hyperbolic discounting and time-inconsistent preference in Laibson (1997), the model of temptation and self-control in Gul and Pesendorfer (2001), the model of addiction and cue-triggered mistake in Bernheim and Rangel (2004), and the dual-self model of impulse control in Fudenberg and Levine (2006).

\textsuperscript{12} VLPFC is bounded superiorly by the inferior frontal sulcus and inferiorly by the lateral sulcus, being attributed to the anatomical structures of Brodmann’s area 47, 45, and 44 (Levy and Wagner, 2011). These regions include the inferior frontal junction, the inferior frontal gyrus, the lateral orbitofrontal gyrus, and the ventral anterior middle frontal gyrus (Cohen, Berkman and Lieberman, 2013; Cohen and Lieberman, 2010). The inferior frontal gyrus can be further divided into three subdivisions: pars opercularis, pars triangularis, and lateral pars orbitalis. The inferior frontal junction is defined as the junction of the inferior frontal sulcus and the inferior precentral sulcus.

\textsuperscript{13} Emotion regulation is the processes in which individuals influence which emotions they have, when they have them, and how they experience and express these emotions (Gross, 1998).
Lieberman (2013) argued that these regions may serve as non-inhibitory self-control related task demands, such as rule monitoring, conflict monitoring, and emotional processing. Additionally, the left VLPFC may be also implicated in self-control (Hare, Camerer and Rangel, 2009), but the involvement of the rVLPFC in many self-control processes is more common than that of the left VLPFC (Cohen, Berkman and Lieberman, 2013; Cohen and Lieberman, 2010). On the other hand, the left VLPFC has been associated more often with the cognitive control specifically of memory (Badre and Wagner, 2007). We, therefore, focus on the region of rVLPFC and posit that exogenously varying self-control by non-invasive brain stimulation over the rVLPFC would casually affect the disposition effect.

3. Materials and Methods

3.1 Experiment Design

The design of our experimental asset market is adapted from Frydman et al. (2014). A subject is endowed with 50 experimental currency units (ECU) and three stocks labeled A, B, and C. The initial price for each stock is 100 ECU. Subjects are given the opportunity to trade the three stocks. The experiment consists of 30 periods. In each period, one stock is randomly chosen and updated its price, while the prices of the other two unchosen stocks remain unchanged. Each stock receives a price update only when it is chosen in a period. In Periods 1 to 6, subjects are not given the opportunity to buy or sell but can observe a price update of one of the three stocks. In Period 7, a subject can decide to sell a stock for the first time. In Periods 8–30 the subject may buy or sell stocks. A subject could trade a stock immediately after observing a price update for the stock.

During the experiment, each subject is only allowed to hold a maximum of one unit of each stock and cannot hold negative units. The short-selling is not allowed. The trading decision in a period is therefore reduced to deciding whether to sell a stock (conditional on holding it) or deciding whether to repurchase it (conditional on not holding it). The price at which a subject can buy or sell a stock is given by the current price in a period. Subjects can carry negative cash balance; hence, buying a stock even if they do not have sufficient cash is possible for them. The amount of
negative cash balance is subtracted from their total payoffs.

A hidden two-state Markov chain with a good state and a bad state determines the price change of each stock. The Markov chains of the three stocks are independent of one another. Before Period 1, the three stocks will be randomly assigned to either a good state or bad state. States are then updated only after a stock is chosen and receives a price update in a period. Specifically, if stock $i$ is in a good state in period $t$, then in period $t+1$, if the price update is not about stock $i$, then the state and price of stock $i$ remains unchanged. However, if the price update is about stock $i$, then the state of stock $i$ in this period remains good with probability 0.8 but switches to bad with probability 0.2. In a good state, the stock increases with probability 0.7 and decreases with probability 0.3. In a bad state, the stock increases with probability 0.3 and decreases with probability 0.7. The magnitude of the price change is drawn uniformly from \{5 ECU, 10 ECU, 15 ECU\}, independently of the direction of the price change. The states of the stocks are always hidden to the subjects, but they can make Bayesian inferences about the state from the observed price change (See the “Theoretical and empirical benchmarks” section below for details).

Following a similar design (Weber and Camerer, 1998; Frydman et al., 2014), we use the same set of realized prices for all subjects, so that it can reduce error in the comparison of trading performance across subjects. Figure 1 exhibits the realized prices of the three stocks.

[Figure 1 here]

To measure subjects’ self-control, we follow Fischbacher, Hoffmann, and Schudy (2017) and ask subjects to pre-specify their ideal capital gains and capital losses limit. Specifically, at the beginning of the experiment subjects must answer “How much capital gains of a hold stock brings to you, you will sell it?” and “How much capital losses of a hold stock brings to you, you will sell it?”. Non-binding limits of capital gains and capital losses are possible, and subjects could not adjust limits during the entire experiment. We also follow Ameriks et al. (2007) and define a variable called actual-ideal consistent (AI-consistent) decision, which is measured by whether the realized (or paper) capital gains (or losses) is consistent with the ideally prespecified
capital gains limit (or losses limit). Self-control is measured with the percentage of AI-consistent decisions. Subjects who have a self-control problem would exhibit lower percentage of AI-consistent decisions.

3.2 Transcranial Direct Current Stimulation (tDCS)

Brain stimulation is applied in a double-blind, sham-controlled manner using a battery-driven stimulator (Neuro Conn, Germany). tDCS is a safe, noninvasive method that allows establishing causal relationships between the circumscribed regions of the brain via electrodes placed on the scalp and their underlying perceptual, cognitive, or motor functions (for reviews, see Nitsche et al., 2008; Filmer, Dux and Mattingley, 2014; Polanía, Nitsche and Ruff, 2018). Anodal and cathodal stimulations are known to increase or decrease the resting potential and therefore neural excitability in the targeted regions, respectively, whereas sham tDCS mimics the peripheral effects associated with tDCS while not affecting neural processing (Nitsche et al. 2008).

We apply anodal, cathodal, or sham tDCS over the rVLPFC region. In line with previous tDCS studies (Riva et al., 2012 and 2015), the stimulation electrode is centered on electrode site F8, according to the standard 10–20 system which corresponds to the rVLPFC. The reference electrode is placed posterior to the left mastoid (Breitling al., 2016). tDCS is applied using a set of standard electrodes fixed by rubber straps (5 cm × 7 cm, current density: 0.029 mA/cm²).

tDCS are applied for 20 minutes with 1 mA current strength for the anodal and cathodal treatment. The sham stimulation electrode arrangement is identical to active stimulation but the stimulator is turned off after 30s. In all treatments, the current is applied with a 15s ramp up and down.

3.3 Subjects and Procedure

Ninety-five healthy college students from Nankai University participated in this study (mean age 22.39 +/- 0.18 [SEM] years, range = 19–26 years, 66 women). Subjects were randomly assigned to one of three stimulation treatments: anodal (n = 31, 20 women), sham (n = 32, 27 women), or cathodal (n = 32, 19 women). Subjects gave informed written consent prior to the study. All experimental procedures were
approved by the local ethics committee.

Prior to the experiment, we randomly assigned each subject to a cubicle. While waiting for the installation of the experiment equipment, a subject filled out a questionnaire that included gender and stock trade experience. After the installation of the experiment equipment, to each subject received 5 minutes of tDCS for ensuring stable stimulation effects (Nitsche et al., 2008). During this stage, we explained the experimental instruction to the subject again.

The entire experiment composed of 30 periods, which lasted for approximately 10 minutes. At the end of the experiment, the subjects’ holdings of the three stocks were liquidated at stock current price and added to cash value. We give subjects a financial incentive to maximize their final payoffs. Specifically, if the total value of a subject’s cash and stock holdings at the end of experiment is $Y$ in ECU, then his take-home payoff is $Y/20$ Chinese yuan, and we add another 10 Chinese yuan ($1.51$) as show-up fee. The average payoff was 45 Chinese yuan ($6.84$) (range: $5.41$–$7.66$, standard deviation: $1.21$).

In addition, we asked subjects to fill out a post-experimental questionnaire that measured their regret and rejoice emotions (Summers and Duxbury, 2012), risk-taking attitudes (Holt and Laury, 2002), and loss aversion (Gächter, Johnson and Herrmann, 2007; Rau, 2014) while the tDCS stimulation was still ongoing. Finally, subjects indicated the extent to which they perceived the stimulation affected their behavior (using a five-point Likert-scale). Subjects gave similar and statistically indistinguishable ratings (mean anodal: 1.51, mean sham: 1.56, mean cathodal: 1.71, and Kruskal-Wallis test, $p = 0.377$).

We conducted the experimental sessions in September 2017 at the Reinhard Selten Laboratory (Sellab) of Nankai University. All experimental sessions were conducted in a treatment room at the Sellab. The group room was laid out with several enclosed cubicles, each of which was equipped with a computer interconnected to a local area network. All the computers had the same hardware and software configurations. This setting was designed to conduct anonymous and randomized experiments. Appendix B exhibits the experiment instructions. The experiment was
programmed using z-Tree (Fischbacher, 2007).

3.4 Theoretical and Empirical Benchmarks

The key aspect of our experiment design is that each of the stocks exhibits positive autocorrelation in its price change (Weber and Camerer, 1998; Frydman et al., 2014). If a stock performs well at its last price update, it is probably in a good state for that price update. As it is highly likely (probability 0.8) for the stock to remain in the same state for its next price update, its next price change is also likely to be positive (probability 0.7).

The risk-neutral Bayesian investor who maximizes the expected value of take-home payoffs could, thus, trade stocks based on the expected price change on the next price update ("Net Expected Value"). That is, a risk-neutral subject will sell stocks whenever the net expected value is negative and will not sell stocks whenever net expected value is positive. The calculation of net expected value is shown in Appendix A. It may be not easy for a subject to do the exact calculation during the experiment. Nevertheless, net expected value is highly correlated with the stock price change (Spearman’s rho = 0.724, p < 0.001). A subject can simply keep track of each stock’s most recent price changes to approximate the optimal trading strategy. Thus, the optimal strategy involves selling stocks that have recently decreased in price and not selling stocks that have recently increased in price, thereby generating the opposite of a disposition effect.


3.5 Measurement of Disposition Effect

The measurement of disposition effect (DE) is computed following Odean’s (1998) methodology. For each period, a stock is counted as “realized gains” ("realized losses") if it is sold at a price higher (lower) than the purchase price, and as “paper gains” (“paper losses”) if it is not sold at a price that is higher (lower) than the purchase price. The total number of realized gains, realized losses, paper gains, and
paper losses across all periods is tallied, and the proportion of gains realized (PGR) and the proportion of losses realized (PLR) are computed as follows:

\[
PGR = \frac{\text{# realized gains}}{\text{# realized gains} + \# paper gains}, \quad PLR = \frac{\text{# realized losses}}{\text{# realized losses} + \# paper losses}.
\]

The size of the DE is the difference between these two ratios (PGR-PLR).

4. Results

We begin our data analysis by testing whether the tDCS over rVLPFC affects the DE. Subsequently, we separate the DE into its two components (PGR and PLR) (Section 4.1). Section 4.2 presents the portfolio choices. Section 4.3 discusses the percentage of AI-consistent decisions across the tDCS treatments. Moreover, Section 4.4 demonstrates the self-control mechanism for the tDCS effect. In our data analysis, all statistical tests involve two-tailed p-values if not otherwise stated.

4.1 Disposition Effect

Figure 2 presents the cumulative distribution (CDF) of DE, PGR, and PLR. Figure 2a shows that the CDF in the cathodal treatment is clearly to the left of the CDF for the sham and anodal treatment. That is, the average DE in the cathodal treatment is \(-0.287\) (SE = 0.062), which is significantly lower than the value of 0.083 (SE = 0.061) in the sham treatment (Kolmogorov–Smirnov test, \(p < 0.001\)) and the value of 0.120 (SE = 0.080) in the anodal treatment (Kolmogorov–Smirnov test, \(p < 0.001\)). By contrast, no significant difference is found between the latter two treatments (Kolmogorov–Smirnov test, \(p = 0.609\)).

**Result 1**: The disposition effect is significantly reduced by cathodal stimulation but left unaltered by anodal or sham stimulation.

Figure 2b shows that the CDF of the PGR in the cathodal treatment first order stochastically dominates the CDF in the sham (Kolmogorov–Smirnov test, \(p = 0.012\)) and anodal treatment (Kolmogorov–Smirnov test, \(p = 0.038\)), whereas the equality of distributions between the latter two treatments cannot be rejected (Kolmogorov–Smirnov test, \(p = 0.698\)). The PGR in the cathodal treatment (\(M = 0.255, SE = 0.036\)) is significantly lower than that in the sham treatment (\(M = 0.356, SE = 0.041\)) and in the anodal treatment (\(M = 0.412, SE = 0.057\)). That is, 71.87% of the subjects in the
cathodal treatment have a PGR < 0.25, whereas only 38.71% of subjects in the anodal treatment and 34.31% of the subjects in the sham treatment are in this range.

Figure 2c also reveals a significant treatment difference in PLR. Specifically, the PLR in the cathodal treatment is 0.542 (SE = 0.049), which is roughly double of the value in the sham treatment (M = 0.273, SE = 0.035) (Kolmogorov–Smirnov test, p < 0.001) and in the anodal treatment (M = 0.292, SE = 0.053) (Kolmogorov–Smirnov test, p < 0.001). 50% of subjects in the cathodal treatment have a PLR > 0.5. By contrast, only 25.80% of subjects in the anodal treatment and 18.75% of subjects in the sham treatment fall into this category. However, no significant difference in PLR is found between the anodal and sham treatments (Kolmogorov–Smirnov test, p = 0.261).

**Result 2:** Cathodal stimulation significantly increases the proportion of losses realized (PLR) and decreases the proportion of gains realized (PGR). Anodal and sham stimulation does not affect PGR and PLR.

4.2 Portfolio Choices

Figure 3 shows the number of held stocks across tDCS treatment. No difference is found in the number of held stocks from Periods 1 to 11 (Kruskal–Wallis test, p = 0.782). Note that before Period 6, subjects are not allowed to trade stocks, and thus the number of held stocks is 3. In Period 11, the number of held stocks decreased to 1.96. This number is stable in the sham and anodal treatments after Period 11.

However, significant treatment differences are found according to the number of held stocks from Periods 12 to 18 and from Periods 19 to 29 (Kruskal-Wallis test, all ps < 0.001). Specifically, subjects in the cathodal treatment slightly increase the number of held stocks from Periods 12 to 18 (i.e., average number is 2.31), and then largely decrease this number from 2.375 in Period 18 to 0.937 in Period 29. Figure 1 suggests that, from Periods 12 to 18, all price updates receive an increase except for Period 18, and it is optimal to hold more stocks. By contrast, from Periods 19 to 29, all price updates receive a decrease except for Periods 27 and 29, and it is optimal to
hold less stocks. These results indicate that the trading decisions in the cathodal treatment are more optimal than those in the anodal and sham treatments.

To understand this development better, Figure 4 separately presents the subjects’ number of held stocks in the sham (a), anodal (b), and cathodal (c) treatments. The average held number of Stock C in the cathodal treatment is 0.781 in Period 11, but it is only 0.484 in the anodal treatment and 0.406 in the sham treatment. The average held number of Stock B in the cathodal treatment decreases to 0.25 in Period 11, whereas it is 0.516 in the anodal treatment and 0.625 in the sham treatment. The average held number of Stock A from Periods 7 to 11 is basically same in the three stimulation treatments (approximately 0.9). These results indicate that before although no treatment difference is observed in the number of held stocks before Period 12, the subjects in the cathodal treatment are quick to sell the loser stock (i.e., Stock B), whereas the subjects in the anodal and sham treatments are quick to sell the winner stock (i.e., Stock C).

In the cathodal treatment, the average held number of Stock B increases from 0.25 in Period 11 to 0.781 in Period 18, for a total increase of 0.531 (i.e., it increased by 0.375 in Period 12 and increased by 0.156 in Period 15). The average held number of Stock C from Periods 12 to 18 is 0.754, which is significantly higher than that in the anodal (0.327) (Kolmogorov–Smirnov test, p = 0.001) and sham treatments (0.397) (Kolmogorov–Smirnov test, p = 0.001).

The average held number of Stocks A, B, and C in cathodal treatment decreases from 0.906 in Period 18 to 0.343 in Period 29, from 0.781 in Period 18 to 0.437 in Period 29, and from 0.687 in Period 18 to 0.156 in Period 29, respectively. However, the average held number of Stocks A, B, and C in the anodal and sham treatment are basically stable after Period 11. The average held number of Stock B from Periods 19 to 29 is 0.541, which is significantly lower than that in the anodal (0.710) (Kolmogorov–Smirnov test, p < 0.001) and the sham treatments (0.718) (Kolmogorov–Smirnov test, p < 0.001).

[Figure 4 here]

In addition, the average held number of Stock B in the cathodal treatment is
0.475 from Periods 7 to 11, which is significantly lower than that of Stock A (0.962) (Wilcoxon signed-rank test, p = 0.055) and Stock C (0.912) (Wilcoxon signed-rank test, p = 0.055). The average held number of Stock C in the anodal and sham treatments is 0.260 and 0.328, respectively, from Periods 12 to 29, which are significantly lower than that of Stock A (Anodal: 0.731, Sham: 0.758) (Wilcoxon signed-rank test, all ps < 0.01) and Stock B (Anodal: 0.709, Sham:0.755) (Wilcoxon signed-rank test, all ps < 0.01).

**Result 3:** Subjects in cathodal treatment are quick to sell loser stock and likely to hold winner stock. Conversely, subjects in anodal or sham treatment are quick to sell winner stock and likely to hold loser stock.

### 4.3 Percentage of Actual-Ideal (AI) Consistent Decision

Figure 5 provides the distribution of capital gains and capital losses limit. The subjects pre-specify significantly lower value of capital losses limit (M = 22.673, SE = 2.158) relative to capital gains limit (M = 36.094, SE = 4.001) (Wilcoxon signed-rank test, p < 0.001). Specifically, 84.21% of the subjects set their capital losses limit below 35, this percent is only 63.15% for the capital gains limit. Moreover, 27.37% of the subjects set their capital gains limit above 35 and below 65, this percent is only 11.58% for the capital losses limit.

[Figure 5 here]

No treatment differences are found in capital gains (Anodal: 33.406±4.820 vs. Sham: 35.967±5.849 vs. Cathodal: 38.906±9.396) and capital losses limit (Anodal: 21.062±2.795 vs. Sham: 23.225±3.706 vs. Cathodal: 23.750±4.595) (Kruskal–Wallis test, all ps > 0.40). However, significant differences are found between the capital gains and capital losses limit in all the three stimulation treatments (Wilcoxon signed-rank test, all ps < 0.001).

Figure 6 depicts the number of decisions that are AI-consistent and AI-inconsistent by stimulation treatment and decision type (realized gains, paper gains, realized losses, and paper losses).

[Figure 6 here]

Subjects with a better self-control would exhibit higher percentage of AI-
consistent decisions and lower percentage of AI-inconsistent decisions. Specifically, if the gain (amount of stock current price beyond its purchase price) is below his or her prespecified capital gains limit, then realized gains is an AI-inconsistent decision and paper gains is an AI-consistent decision. If the loss (amount of stock current price under its purchase price) is below his or her prespecified capital losses limit, then realized losses is an AI-inconsistent decision and paper losses is an AI-consistent decision (see Table 1).

[Table 1 here]

The chart in Figure 6 shows that the cathodal treatment primarily affects behavior through the paper losses and paper gains channels. That is, the DE is attenuated because of a significant reduction in paper losses (Anodal: 212 vs. Sham: 239 vs. Cathodal: 109) (Kruskal–Wallis test, p < 0.001) and a significant increase in paper gains (Anodal: 118 vs. Sham: 118 vs. Cathodal: 183) (Kruskal–Wallis test, p < 0.001).

Importantly, the percentage of AI-consistent decisions in the cathodal treatment (52.92% ± 4.20%) is significantly higher than that in the anodal (41.64% ± 3.65%) and sham treatments (41.99% ± 3.18%) (Kolmogorov–Smirnov test, all ps < 0.001) (Figure 7). However, no significant difference is found in the percentage of AI-consistent decisions between the anodal and sham treatments (Kolmogorov–Smirnov test, p = 0.895). Subjects in cathodal treatment have more percentage of AI-consistent decisions in the realized gains (Anodal: 46.15% vs. Sham: 54.90% vs. Cathodal: 68.96%), paper gains (Anodal: 30.51% vs. Sham: 22.88% vs. Cathodal: 43.71%), and paper losses channels (Anodal: 43.86% vs. Sham: 43.51% vs. Cathodal: 51.37%). Interestingly, no treatment difference is observed in the percentage of AI-consistent decisions in the realized losses channel (Anodal: 52.94% vs. Sham: 58.21% vs. Cathodal: 55.17%).

Furthermore, we find that the percentage of AI-consistent decisions is negatively correlated with the DE (r = −0.420, p < 0.001) and the PGR (r = −0.219, p = 0.030), but it is positively correlated with the PLR (r = 0.416, p < 0.001).

[Figure 7 here]
**Result 4**: Cathodal stimulation significantly increases the percentage of AI-consistent decisions. The percentage of AI-consistent decisions is correlated with disposition effect, PGR, and PLR.

### 4.4 Self-control Mechanism

First, we run logistic regressions in which we define *anodal* and *cathodal* as dummy variables that are both set to 1 if the individual received anodal or cathodal stimulation, or to 0 in all other cases. *Sell* is a dummy variable that equals 1 if the subject sells a stock and equals 0 if the subject holds it conditional on the opportunity to sell. *Net Expected Value* is the expected future price change of the stock conditional on all previous information. *Gain* is the standardized capital gain that is calculated by subtracting stock purchase price from stock current price. Cathodal×Gain is the interaction term of the variable *cathodal* and *gain*. Anodal×Gain is the interaction term of the variable *anodal* and *gain*.

Table 2 shows that the coefficient for the capital gain in Column (1a) is positive and significant. Crucially, the coefficients of cathodal×gain in Columns (1b) and (1d) are negative and significant. Meanwhile, the coefficients of anodal×gain in Columns (1b) and (1d) are insignificant. Cathodal stimulation negatively moderates the relationship of capital gains and propensity to sell a stock. That is, in the cathodal treatment, capital gains have a weak influence on propensity to sell a stock. These results indicate that cathodal stimulation reduces the DE by moderating the effect of capital gains on the propensity to sell stocks.

[Table 2 here]

Second, Table 3 shows the results of OLS regressions, in which we define *anodal* and *cathodal* as dummy variables that are set to 1 if the individual received anodal or cathodal stimulation or to 0 in all other cases. We include individual characteristics, such as the subjects’ gender (using a *woman* dummy) and stock trading experience (using an *experience* dummy), as well as the subjects’ prespecified *capital gains limit* (standardized) and *capital losses limit* (standardized) as control variables.

[Table 3 here]

Models (1a), (2a), and (3a) also confirm the non-parametric tests. Thus, cathodal...
stimulation significantly reduces the DE. Moreover, this effect is primarily driven by cathodal stimulation significantly decreasing the PGR and significantly increasing the PLR. Our findings are robust even if we control for individual characteristics, capital gains limit, and capital losses limit in Models (1b), (2b), and (3b), such that the coefficients and significant levels for cathodal stimulation are basically unchanged.

In Models (1c), (2c), and (3c), we include the subjects’ percentage of AI-consistent decisions. The coefficients for percentage of AI-consistent decisions are all statistically significant, which is in line with the prior correlation analysis. Moreover, the coefficients for cathodal stimulation in Models (1c) and (3c) become small and significant, whereas the coefficients for cathodal stimulation in Model (2c) become small and insignificant. These results are robust when we control for individual characteristics, capital gains limit, and capital losses limit in Models (1d), (2d), and (3d).

In Models (4a) and (4b), we examine the effect of cathodal stimulation on the percentage of AI-consistent decisions. In accordance with the non-parametric test, we elucidate that cathodal stimulation significantly increases the percentage of AI-consistent decisions even if we control for individual characteristics, capital gains limit, and capital losses limit. The subjects’ capital gains limit has a negative effect on the percentage of AI-consistent decisions, whereas the capital losses limit has a positive effect.

Therefore, a conspicuous finding involves the presence of a significant indirect path from cathodal stimulation through the percentage of AI-consistent decisions to the DE, PGR, and PLR (Baron and Kenny, 1986). In this case, we reveal that the coefficients of cathodal stimulation are positive and significant at 10% level in Models (4a) and (4b). Hence, the cathodal stimulation effect on the DE, PGR, and PLR is mediated by the percentage of AI-consistent decisions.

[Figure 8 here]

**Result 5:** Subjects’ percentage of AI-consistent decisions mediates the effect of cathodal stimulation on disposition effect, PGR and PLR.

Taken together, we find that cathodal stimulation significantly reduces the DE
(Result 1), and this effect is mediated by self-control which is measured with the percentage of AI-consistent decisions (Result 5). This result reflects three behavioral aspects. First, and most importantly, subjects in the cathodal stimulation treatment have a low PGR and a high PLR (Result 2). Second, subjects are quick to sell loser stock and likely to hold winner stock in the cathodal stimulation treatment (Result 3). Third, subjects in the cathodal stimulation treatment exhibit a higher percentage of AI-consistent decisions (Result 4).

5. Robustness Check

We show that cathodal tDCS over rVLPFC reduces the disposition effect and the underlying mechanism for this effect is exhibiting sufficient self-control, which is represented by a high percentage of AI-consistent decisions. Here, we discuss whether the stimulated neural process reflects other forms of control, such as control over emotion, control over risk-taking attitude or loss aversion, control over cognitive dissonance, and control over belief in mean reversion.

5.1 Regret and Rejoice

Lehenkari (2012) and Summers and Duxbury (2012) show that regret affects the DE. Cathodal tDCS over rVLPFC might have reduced the DE through enhancement of emotion regulation.

We test this possibility by collecting the regret and rejoice introduced in Summers and Duxbury (2012). Regret and rejoice data are collected by asking subjects “How regretful are you about your decision, when the stock you purchased has decreased in value compared to the previous period?” and “How rejoiced are you about your decision, when the stock you purchased has increased in value compared to the previous period?” Levels of the regret and rejoice are measured on a 1–9 scale (1 = not at all, 9 = very much).

In Table 4, we show that tDCS does not have any influence on rejoice (Kruskal–Wallis test, p = 0.545) but has marginal influence on regret (Kruskal–Wallis test, p = 0.066). Subjects report a significant lower degree of regret in the anodal stimulation (M = 3.61, SE = 0.15) than in the sham (M = 3.93, SE = 0.14) and cathodal
stimulations (M = 4.00, SE = 0.14). No significant difference is found in the regret between the sham and cathodal stimulations (Kolmogorov–Smirnov test, p = 1.00). Furthermore, OLS regressions in Tables 5 and 6 indicate that the effect of cathodal tDCS remains significant for controlling regret and rejoice.

5.2 Risk-Taking Attitude and Loss Aversion

It has been found that activity in the rVLPFC is correlated with risk-taking attitude (Christopoulos et al., 2009). tDCS stimulation might have changed a subject’s risk-taking attitude and tendency for loss aversion, which in turn might have led to a reduction of the DE (Imas, 2016; Rau, 2014).

During tDCS, a subject is asked to choose between Options A and B for each of the 10 paired lottery choices of Holt and Laury (2002). The total number of “safe” “A” choices is used as an indicator of risk aversion. A subject’s loss aversion is determined using the elicitation task of Rau (2014). In this task, 10 different lottery choices exist. The lotteries are framed such that a certain amount of money is lost if a coin landed on “heads” whereas subjects win 10 yuan if the coin lands on “tails.” The loss increases with each lottery from 2 to 11 yuan, whereas the winning payoff is constant. For each of the 10 lotteries, the subject states whether he or she accepts it. We record the switching point when the subject stops accepting the lotteries. Based on the switching point, we calculate the loss-aversion coefficient (λ), which follows $\lambda = \frac{V(G)}{V(L)}$, where $V(G)$ and $V(L)$ represent the potential gain/losses of the lottery which is rejected (Gächter, Johnson and Herrmann, 2007). Lambda is defined between 0.91 and 5. If a subject accepts all the lotteries, then his loss-aversion coefficient is $\lambda = \frac{V(10)}{V(2)}=10/2=5$. If a subject rejects all the lotteries, then his loss aversion coefficient is $\lambda = \frac{V(10)}{V(11)}=10/11=0.91$.

No significant differences are found on the risk and loss aversion of the three tDCS stimulations (Kruskal–Wallis test, all ps > 0.50). Results in Tables 7 and 8
highlight that adding risk and loss aversion to the regression model does not change the significance of cathodal tDCS. In sum, we find no indication that risk-taking attitude and loss aversion affected the DE, PGR, and PLR in the cathodal tDCS.

5.3 Cognitive Dissonance

Chang, Solomon, and Westereld (2016) demonstrated the role of cognitive dissonance in generating the DE, which is supported by evidence of investors avoiding realizing capital losses because they dislike admitting that past purchases were mistakes, whereas delegation reverses the DE by allowing the investor to blame the manager instead. Cathodal stimulation may control over cognitive dissonance and thus reduces the DE.

Panel (c) in Figure 5 shows that before Period 17 the average held number of Stock A is all above 0.90 in the cathodal treatment, indicating that subjects almost do not sell the initially endowed Stock A. The average held number of Stock B largely decreased to 0.25 in Period 11 and increased to 0.781 in Period 17. Thus, compared with Stock A, most of Stock B is purchased by the subjects themselves. Figure 1 shows that both Stock A and Stock B are updated by a decrease in price from Period 18 to Period 25. If cathodal stimulation changes the subjects’ cognitive dissonance, from Period 18 to Period 25 we would observe the same propensity for selling both the Stock A and Stock B. However, a significant difference is found in the average held numbers of Stock A (0.437) and Stock B (0.586) from Period 18 to Period 25 (Kolmogorov–Smirnov test, p=0.051). This result indicates that subjects in the cathodal stimulation treatment are more likely to sell the endowed Stock A than the Stock B purchased by themselves, suggesting cathodal stimulation does not exert control over cognitive dissonance.

5.4 Belief in Mean Reversion

Finally, previous fMRI studies have found evidence that the DE is driven by a belief that the stock will eventually return to the purchase price (Brooks, Capra and Berns, 2012). Subjects who irrationally believe prices exhibit mean reversion will hold recent losers and sell recent winners. Cathodal tDCS over rVLPFC could change the subjects’ belief in mean reversion, and thus reduce the DE.
We follow Weber and Camerer (1998) and test this explanation by analyzing the subjects’ purchase behavior. In our experiment, the initial purchase price of Stock A, Stock B, and Stock C is 100, which would be naturally regarded as the reference price for the purchase of a stock. If cathodal stimulation affects belief in mean reversion, we would observe a decrease in purchasing stock whose price is below 100 (e.g., Stock B) and an increase in purchasing stock whose price is above 100 (e.g., stock C). However, in the 24 trading periods, the average held number of winner Stock C in the three stimulation treatments all show a downward trend (see Figure 5). In addition, Panel (a) in Figure 5 shows that in sham stimulation the average held number of Stock B increase from 0.625 in Period 11 to 0.906 in Period 16. Panel (b) in Figure 5 depicts that in anodal stimulation the average held number of Stock B increases from 0.516 in Period 11 to 0.774 in Period 16. Panel (c) in Figure 5 illustrates that in cathodal stimulation the average held number of Stock B increases from 0.25 in Period 11 to 0.781 in Period 16. Subjects in the cathodal stimulation treatment are more likely to purchase the loser Stock B. These results rule out the possibility that cathodal stimulation changes the belief in mean reversion.

6. Discussion

In this paper we apply tDCS over rVLPFC while subjects trade in an experimental stock market to causally test the impact of self-control on investor behavior. Our tDCS study provides broad (albeit not perfect) support for the role of self-control in the disposition effect. First and the most important, we find that cathodal stimulation over rVLPFC, an area known to encode different forms of self-control, causally reduce the disposition effect by helping investors exhibit a sufficient self-control, which is represented by a high percentage of actual-ideal consistent decision. Second, we document that investors in the cathodal stimulation treatment are quick to sell loser stock and likely to hold winner stock, and thus have a lower proportion of gains realized (PGR) and a higher proportion of losses realized (PLR). These findings are striking because it would be extremely difficult to conduct such a causal test without using non-invasive brain stimulation.

Although cathodal stimulation over rVLPFC had a critical impact on the
disposition effect, we posit that it is unlikely that rVLPFC is the only factor that drives this effect. Instead, rVLPFC stimulation might have altered the crosstalk of rVLPFC and other areas that are critical for decision making, particularly the ventromedial prefrontal cortex (vmPFC). vmPFC has been shown to be involved in the computation of the value of available options (Tom et al., 2007). Frydman et al. (2014) find that subjects whose vmPFC activity is more correlated with the realizable capital gain have a stronger disposition effect, thereby demonstrating the realizing utility model. We speculate that rVLPFC might override vmPFC activity and help investors exhibit sufficient self-control by adapting the reference point to the prespecified capital gains (or losses) limit and thus attenuating the preference of realizing utility (Barberis and Xiong, 2012).14

The adaptation of the reference point plays an important role in stock trading decisions (Arkes et al., 2008; Baucells, Weber and Welfens, 2011). Birru (2015) proved that investor failure to update reference prices following the nominal change in stock prices caused by stock splits leads to a reduction of the disposition effect. Frydman, Hartzmark, and Solomon (2018) documented that the disposition effect would be reduced when investors sell one stock and quickly buy another one, mainly because of the rolling of the purchase price of the sold stock into the new stock. Adaptation of reference point may be one of the underlying mechanisms for the role of self-control in the disposition effect.

Overall, our results support the important role of self-control in the investor behavior and provide evidence that dual-self model of impulse control is an explanation for the disposition effect (Thaler and Shefrin, 1981; Fudenberg and Levine, 2006). Richards et al. (2018) showed that investors with high reliance on intuitive processes have greater disposition effect, but reliance on reflective processes is not related to the disposition effect. We document that cathodal stimulation significantly moderates the propensity of realizing capital gains and elevates the

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14 Such a modulating influence of the lateral prefrontal cortex on vmPFC activity has also been suggested by other studies that examined other forms of self-control decisions (e.g., Hare et al. 2009).
propensity of realizing capital losses, suggesting that reflective or rational processes based on calculative reasoning is more involved in the stock trading decision.

At last, tDCS is a non-invasive brain stimulation enabling researchers to directly study how experimentally-altered neural activity causally affects behavior (Polania, Nitsche and Ruff, 2018). This unique property of the tDCS has led to groundbreaking findings on the neurobiological mechanisms underlying individual behavior (e.g., Ruff and Fehr, 2013; Maréchal et al., 2017). We argue that non-invasive brain stimulation is a helpful and complementary tool that can be applied to causally test the underlying mechanism of investor behavior, which is difficult to evaluate using the method of questionnaire or experiment alone.

In this paper, we demonstrate that tDCS can be applied to causally test the role of self-control in investor behavior. We find that cathodal stimulation of rVLPFC increases the percentage of actual-ideal consistent decisions. Such polarity-specific effect of stimulation, and more specifically, such improvements in cognitive task following an inhibitory (cathodal) stimulation protocol have also been documented by other tDCS studies (e.g., Dockery et al., 2009; Moos et al., 2012; Weiss and Lavidor, 2012; Filmer, Mattingley and Dux, 2013). For example, in line with our results, Moos et al. (2012) also found that cathodal stimulation (2 mA) significantly enhanced the top-down control of visual attention and speculated that the often reported inhibitory effect of cathodal stimulation in the motor tasks might not extend to cognitive paradigms. One possibility is that inhibition suppresses neural noise, reducing the signal-to-noise ratio in the stimulated cortex (Miniussi, Harris and Ruzzoli, 2013; Filmer, Dux and Mattingley, 2014). This explanation means that the rVLPFC might inhibit the intuitive or impulsive behavior through the crosstalk of the vmPFC, and thus help investors involve in goal-directed behavior. However, there is no compelling evidence for facilitation following an inhibitory stimulation protocol, and the precise mechanism underlying such effects remain unclear.
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Figure 1. Realized prices used in the experiment. The price of each stock is updated 10 times. Stock A is updated five times for price increase and five times for price decrease. The realized price of Stock A is shown in black. Stock B is updated seven times for price increase and three times for price decrease. The realized price of Stock B is shown in red. Stock C is updated three times for price increase and seven times for price decrease. The realized price of Stock C is shown in green. Subjects who follow the optimal strategy would sell Stock B in Period 7, buy Stock B in Period 12, sell Stock A in Period 18, sell Stock B in Period 19, sell Stock C in Period 20, buy Stock A in Period 27, sell Stock A in Period 28, and buy Stock B in Period 29.
Figure 2. Distributions of Disposition Effect, PGR, and PLR across tDCS treatment. Panel (a) is the cumulation distributions of disposition effect in the three stimulation treatments; Panel (b) is the cumulation distributions of PGR in the three stimulation treatments; and Panel (c) is the cumulation distributions of PLR in the three stimulation treatments.
Figure 3. **Number of held stocks across tDCS treatment.** Compared with sham or anodal treatment, for the cathodal treatment the number of held stocks is essentially the same from Periods 1 to 11, then slightly increases from Periods 12 to 18, but largely decreases from 2.375 in Period 18 to 0.937 in Period 29.

![Graph showing the number of held stocks across tDCS treatment](image)

Figure 4. **Number of held stocks during the sham, anodal, and cathodal stimulations.** Panel (a) is the average hold number of every stock in each period for the sham stimulation treatment; Panel (b) is the average hold number of every stock in each period for the anodal stimulation treatment; and Panel (c) is the average hold number of every stock in each period for the cathodal stimulation treatment.

![Graphs showing the number of held stocks during different stimulations](image)
Figure 5. Distributions of capital gains and capital losses limit. The distribution of capital gains limit is in the left panel; the distribution of capital losses limit is in the right panel.

Figure 6. Selling behavior disaggregated by decision type across tDCS treatment. Data are binned according to whether the decision was AI-consistent or AI-inconsistent, and whether it was generated from the anodal, sham, or cathodal treatment. Realized gains is AI-inconsistent when the gains received by the subject from selling the stock is below his or her prespecified capital gains limit. Paper gains is AI-consistent when the paper gain is below his or her prespecified capital gains limit. Realized losses is AI-inconsistent when the losses received by the subject from selling the stock is below his or her prespecified capital losses limit. Paper losses is AI-consistent when the paper loss is below his or her prespecified capital losses limit.
Figure 7. Impact of tDCS on the percentage of actual-ideal (AI) consistent decision in the three stimulation treatments. The percentage of AI is calculated as the percentage of actual-ideal consistent decisions in the four decision types. Error bars indicate ±1 SEM.
Figure 8. Schematic diagram of mediation analysis results for the disposition effect. Reported path values are unstandardized regression coefficients with standard errors in parentheses. Data in grey color represent results when including covariates (Woman, Experience, Capital gains limit, Capital losses limit) in regressions. Significance levels: *p < 0.10, **p < 0.05, ***p < 0.01.

\[ c = -0.371^{**}(0.087) \]
\[ c' = -0.298^{**}(0.088) \]
\[ a = 0.109^{**}(0.052) \]
\[ b = -0.659^{***}(0.206) \]
Table 1. Actual-ideal inconsistent and actual-ideal consistent decisions in the four decision types. Gain is the amount of stock current price beyond its purchase price. Loss is the amount of stock current price under its purchase price. Limit is the subjects’ prespecified capital gains or losses limit.

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Table 2. Logit regression of subjects’ propensity to sell a stock. Dependent variable is Sell equals 1 if the subject sells a stock and equals 0 if the subject holds it (conditional on the opportunity to sell). Gain is the standardized capital gain that is calculated by subtracting stock purchase price from stock current price. Net Expected Value is the expected future price change of the stock conditional on all previous information. Anodal (1 = anodal, 0 = others) and Cathodal (1 = cathodal, 0 = others) are dummy variables. Logit regression is with robust standard errors (clustering at the individual level). Robust standard error is displayed in parentheses. Significance levels: *p < 0.10, **p < 0.05, ***p < 0.01.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>(1a)</th>
<th>(1b)</th>
<th>(1c)</th>
<th>(1d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Expected Value</td>
<td>−0.519***</td>
<td>−0.537***</td>
<td>−0.520***</td>
<td>−0.541***</td>
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<tr>
<td></td>
<td>(0.088)</td>
<td>(0.090)</td>
<td>(0.089)</td>
<td>(0.089)</td>
</tr>
<tr>
<td>Gain</td>
<td>0.591***</td>
<td>0.907***</td>
<td>0.475***</td>
<td>0.962***</td>
</tr>
<tr>
<td>(standardized)</td>
<td>(0.107)</td>
<td>(0.156)</td>
<td>(0.116)</td>
<td>(0.157)</td>
</tr>
<tr>
<td>Cathodal</td>
<td></td>
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<td></td>
</tr>
<tr>
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<td>0.287</td>
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<td>0.211</td>
<td>0.182</td>
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<tr>
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<td>(0.166)</td>
<td>(0.166)</td>
<td>(0.166)</td>
<td>(0.182)</td>
</tr>
<tr>
<td>Cathodal × Gain</td>
<td>−0.859***</td>
<td>−0.910***</td>
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</tr>
<tr>
<td></td>
<td>(0.193)</td>
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<tr>
<td>Anodal</td>
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<td>(0.173)</td>
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<td>Anodal × Gain</td>
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<tr>
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<td>(0.266)</td>
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<td>(0.073)</td>
<td>(0.096)</td>
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<td>Pseudo R²</td>
<td>0.034</td>
<td>0.062</td>
<td>0.040</td>
<td>0.063</td>
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</table>
Table 3. Effect of tDCS on PGR, PLR, and disposition effect (DE). OLS regression is with robust standard errors (clustering at the individual level). Robust standard error is displayed in parentheses. Significance levels: *p < 0.10, **p < 0.05, ***p < 0.01. Anodal (1 = anodal, 0 = others), Cathodal (1 = cathodal, 0 = others) and Woman (1 = female, 0 = male) are dummy variables. Experience is a dummy variable, which is set to 1 if a subject has stock trading experience, and 0 otherwise. Percentage of AI-consistent decision is the subjects’ percentage of actual-ideal consistent decisions. Capital gains limit is the standardized prespecified capital gains. Capital losses limit is the standardized prespecified capital losses.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>DE (1a)</th>
<th>DE (1b)</th>
<th>DE (1c)</th>
<th>DE (1d)</th>
<th>PGR (2a)</th>
<th>PGR (2b)</th>
<th>PGR (2c)</th>
<th>PGR (2d)</th>
<th>PLR (3a)</th>
<th>PLR (3b)</th>
<th>PLR (3c)</th>
<th>PLR (3d)</th>
<th>Percentage of AI-consistent decision (4a)</th>
<th>Percentage of AI-consistent decision (4b)</th>
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<td>Anodal</td>
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<td>0.034</td>
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<td>0.055</td>
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<td>0.054</td>
<td>0.059</td>
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<td>−0.001</td>
<td>0.020</td>
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<td>(0.098)</td>
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<td>(0.074)</td>
<td>(0.068)</td>
<td>(0.072)</td>
<td>(0.063)</td>
<td>(0.065)</td>
<td>(0.060)</td>
<td>(0.062)</td>
<td>(0.048)</td>
<td>(0.050)</td>
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<td>−0.341***</td>
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<td>−0.101**</td>
<td>−0.092*</td>
<td>−0.077</td>
<td>−0.063</td>
<td>0.269***</td>
<td>0.250***</td>
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<td>0.202***</td>
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<td>(0.088)</td>
<td>(0.088)</td>
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<td>(0.058)</td>
<td>(0.054)</td>
<td>(0.055)</td>
<td>(0.060)</td>
<td>(0.061)</td>
<td>(0.063)</td>
<td>(0.052)</td>
<td>(0.049)</td>
<td>(0.049)</td>
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<tr>
<td>Woman</td>
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<td>−0.709***</td>
<td>−0.215*</td>
<td>−0.270*</td>
<td>−0.444***</td>
<td>−0.438**</td>
<td>0.444***</td>
<td>0.438**</td>
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<td>Experience</td>
<td>0.113</td>
<td>0.078</td>
<td>0.011</td>
<td>0.002</td>
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<td>−0.081</td>
<td>−0.017</td>
<td>−0.036</td>
<td>0.022</td>
<td>−0.134***</td>
<td>0.092**</td>
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<tr>
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<td>(0.066)</td>
<td>(0.065)</td>
<td>(0.059)</td>
<td>(0.062)</td>
<td>(0.047)</td>
<td>(0.047)</td>
<td>(0.066)</td>
<td>(0.040)</td>
<td>(0.043)</td>
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<td>(0.066)</td>
<td>(0.040)</td>
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<tr>
<td>Capital gains</td>
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<td>0.071</td>
<td>0.046</td>
<td>0.022</td>
<td>0.066</td>
<td>0.092**</td>
<td>0.043</td>
<td>0.056</td>
<td>0.017</td>
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<td></td>
</tr>
<tr>
<td>limit (standardized)</td>
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<td>(0.081)</td>
<td>(0.081)</td>
<td>(0.081)</td>
<td>(0.107)</td>
<td>(0.102)</td>
<td>(0.062)</td>
<td>(0.150)</td>
<td>(0.150)</td>
<td>(0.150)</td>
<td>(0.150)</td>
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<tr>
<td>Capital losses</td>
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<td>0.017</td>
<td>−0.023</td>
<td>0.092**</td>
<td>0.043</td>
<td>0.453***</td>
<td>0.433***</td>
<td>0.419***</td>
<td>0.453***</td>
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<td></td>
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<tr>
<td>limit (standardized)</td>
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<td>(0.079)</td>
<td>(0.049)</td>
<td>(0.046)</td>
<td>(0.045)</td>
<td>(0.062)</td>
<td>(0.062)</td>
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<td>(0.062)</td>
<td>(0.062)</td>
<td>(0.062)</td>
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</tr>
<tr>
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<td>0.356***</td>
<td>0.343***</td>
<td>0.446***</td>
<td>0.465***</td>
<td>0.273***</td>
<td>0.273***</td>
<td>0.351***</td>
<td>0.152</td>
<td>0.419***</td>
<td>0.453***</td>
</tr>
<tr>
<td></td>
<td>(0.061)</td>
<td>(0.105)</td>
<td>(0.104)</td>
<td>(0.155)</td>
<td>(0.041)</td>
<td>(0.077)</td>
<td>(0.068)</td>
<td>(0.095)</td>
<td>(0.031)</td>
<td>(0.073)</td>
<td>(0.058)</td>
<td>(0.115)</td>
<td>(0.032)</td>
<td>(0.048)</td>
</tr>
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<td>95</td>
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<td>95</td>
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<td>95</td>
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<td></td>
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</tr>
<tr>
<td>R²</td>
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<td>0.220</td>
<td>0.295</td>
<td>0.323</td>
<td>0.062</td>
<td>0.099</td>
<td>0.138</td>
<td>0.186</td>
<td>0.222</td>
<td>0.288</td>
<td>0.309</td>
<td>0.061</td>
<td>0.183</td>
<td></td>
</tr>
</tbody>
</table>
Table 4. Summary of statistics testing for possible stimulation treatment differences in variables that may have affected disposition effect. Risk aversion is the number of safe choices (0 to 10) subjects chose. Loss aversion is the value of lambda ranging between 0.9 (lowest degree) and 5 (highest degree).

<table>
<thead>
<tr>
<th></th>
<th>Anodal (N = 31)</th>
<th>Sham (N = 32)</th>
<th>Cathodal (N = 32)</th>
<th>Total (N = 95)</th>
<th>Kruskal–Wallis (p value)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SEM</td>
<td>M</td>
<td>SEM</td>
<td>M</td>
</tr>
<tr>
<td>Regret</td>
<td>3.61</td>
<td>0.15</td>
<td>3.93</td>
<td>0.14</td>
<td>4.00</td>
</tr>
<tr>
<td>Rejoice</td>
<td>4.90</td>
<td>0.08</td>
<td>4.75</td>
<td>0.11</td>
<td>4.78</td>
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<tr>
<td>Risk aversion</td>
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<td>5.53</td>
<td>0.36</td>
<td>5.93</td>
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<td>Loss aversion</td>
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<td>0.08</td>
<td>1.63</td>
<td>0.09</td>
<td>1.59</td>
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</table>
Table 5. Effect of tDCS on PGR, PLR, and disposition effect (DE) do not reflect regret.
OLS regression is with robust standard errors (clustering at the individual level). Robust standard error is displayed in parentheses. Significance levels: *p < 0.10, **p < 0.05, ***p < 0.01.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>DE (1a)</th>
<th>DE (1b)</th>
<th>PGR (2a)</th>
<th>PGR (2b)</th>
<th>PLR (3a)</th>
<th>PLR (3b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anodal</td>
<td>0.054</td>
<td>0.084</td>
<td>0.070</td>
<td>0.078</td>
<td>0.015</td>
<td>−0.005</td>
</tr>
<tr>
<td></td>
<td>(0.103)</td>
<td>(0.107)</td>
<td>(0.073)</td>
<td>(0.076)</td>
<td>(0.066)</td>
<td>(0.067)</td>
</tr>
<tr>
<td>Cathodal</td>
<td>−0.374***</td>
<td>−0.345***</td>
<td>−0.104**</td>
<td>−0.095*</td>
<td>0.270***</td>
<td>0.249***</td>
</tr>
<tr>
<td></td>
<td>(0.086)</td>
<td>(0.091)</td>
<td>(0.054)</td>
<td>(0.058)</td>
<td>(0.060)</td>
<td>(0.062)</td>
</tr>
<tr>
<td>Regret</td>
<td>0.054</td>
<td>0.060</td>
<td>0.044</td>
<td>0.046</td>
<td>−0.009</td>
<td>−0.013</td>
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<td>(0.044)</td>
<td>(0.034)</td>
<td>(0.032)</td>
<td>(0.032)</td>
<td>(0.034)</td>
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<tr>
<td>Woman</td>
<td>0.113</td>
<td>0.100</td>
<td></td>
<td></td>
<td>−0.102*</td>
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<td></td>
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<td>(0.065)</td>
<td></td>
<td></td>
<td>(0.058)</td>
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</tr>
<tr>
<td>Experience</td>
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<td>(0.079)</td>
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<td>(0.110)</td>
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<tr>
<td>Capital gains limit (standardized)</td>
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<td>(0.052)</td>
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<tr>
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<td>−0.070</td>
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<td>(0.049)</td>
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<td>(0.145)</td>
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<td>(0.146)</td>
</tr>
<tr>
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<td>95</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>R²</td>
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<td>0.080</td>
<td>0.118</td>
<td>0.187</td>
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Table 6. Effect of tDCS on PGR, PLR, and disposition effect (DE) do not reflect rejoice.
OLS regression is with robust standard errors (clustering at the individual level). Robust standard error is displayed in parentheses. Significance levels: *p < 0.10, **p < 0.05, ***p < 0.01.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>DE (1a)</th>
<th>DE (1b)</th>
<th>PGR (2a)</th>
<th>PGR (2b)</th>
<th>PLR (3a)</th>
<th>PLR (3b)</th>
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<tbody>
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<td>0.048</td>
<td>0.054</td>
<td>0.032</td>
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<td>(0.069)</td>
<td>(0.072)</td>
<td>(0.065)</td>
<td>(0.067)</td>
</tr>
<tr>
<td>Cathodal</td>
<td>−0.375***</td>
<td>−0.345***</td>
<td>−0.102*</td>
<td>−0.094*</td>
<td>0.272***</td>
<td>0.251***</td>
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<td>(0.093)</td>
<td>(0.056)</td>
<td>(0.059)</td>
<td>(0.059)</td>
<td>(0.061)</td>
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<tr>
<td>Rejoice</td>
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<td>0.137**</td>
<td>0.047</td>
<td>0.054</td>
<td>−0.088**</td>
<td>−0.082*</td>
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<td>(0.064)</td>
<td>(0.036)</td>
<td>(0.036)</td>
<td>(0.043)</td>
<td>(0.044)</td>
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<td>Woman</td>
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<td>0.008</td>
<td></td>
<td></td>
<td>−0.098*</td>
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<td></td>
<td>(0.087)</td>
<td>(0.065)</td>
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<td></td>
<td>(0.057)</td>
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</tr>
<tr>
<td>Experience</td>
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<td>0.055</td>
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</tr>
<tr>
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<td>(0.092)</td>
<td>(0.076)</td>
<td></td>
<td></td>
<td>(0.113)</td>
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<td></td>
<td>(0.046)</td>
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<td>Capital losses limit (standardized)</td>
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<td>(0.046)</td>
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</tr>
<tr>
<td>R²</td>
<td>0.233</td>
<td>0.261</td>
<td>0.075</td>
<td>0.116</td>
<td>0.224</td>
<td>0.255</td>
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</tbody>
</table>
### Table 7. Effect of tDCS on PGR, PLR, and disposition effect (DE) do not reflect risk aversion. OLS regression is with robust standard errors (clustering at the individual level). Robust standard error is displayed in parentheses. Significance levels: *p < 0.10, **p < 0.05, ***p < 0.01.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>DE (1a)</th>
<th>DE (1b)</th>
<th>PGR (2a)</th>
<th>PGR (2b)</th>
<th>PLR (3a)</th>
<th>PLR (3b)</th>
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<tr>
<td>Anodal</td>
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<td>0.044</td>
<td>0.052</td>
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<td></td>
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<td>(0.070)</td>
<td>(0.072)</td>
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<td>(0.065)</td>
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<tr>
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<td>-0.112**</td>
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<td>0.269***</td>
<td>0.249***</td>
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<tr>
<td></td>
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<td>(0.089)</td>
<td>(0.052)</td>
<td>(0.054)</td>
<td>(0.062)</td>
<td>(0.063)</td>
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<tr>
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<td>0.027*</td>
<td>0.027*</td>
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<tr>
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<tr>
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<td>(0.059)</td>
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</tr>
<tr>
<td>Experience</td>
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</tr>
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</tr>
<tr>
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<td>(0.049)</td>
<td>(0.047)</td>
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<td>Capital losses limit</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(standardized)</td>
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<td>(0.046)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
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<td>-0.166</td>
<td>0.207***</td>
<td>0.186</td>
<td>0.273***</td>
<td>0.353***</td>
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<tr>
<td></td>
<td>(0.146)</td>
<td>(0.171)</td>
<td>(0.095)</td>
<td>(0.104)</td>
<td>(0.089)</td>
<td>(0.104)</td>
</tr>
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<td>95</td>
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</tr>
<tr>
<td>R²</td>
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<td>0.237</td>
<td>0.104</td>
<td>0.143</td>
<td>0.186</td>
<td>0.222</td>
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</table>

### Table 8. Effect of tDCS on PGR, PLR, and disposition effect (DE) do not reflect loss aversion. OLS regression is with robust standard errors (clustering at the individual level). Robust standard error is displayed in parentheses. Significance levels: *p < 0.10, **p < 0.05, ***p < 0.01.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>DE (1a)</th>
<th>DE (1b)</th>
<th>PGR (2a)</th>
<th>PGR (2b)</th>
<th>PLR (3a)</th>
<th>PLR (3b)</th>
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<td>Anodal</td>
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<td>(0.068)</td>
<td>(0.070)</td>
<td>(0.065)</td>
<td>(0.066)</td>
</tr>
<tr>
<td>Cathodal</td>
<td>-0.368***</td>
<td>-0.336***</td>
<td>-0.098*</td>
<td>-0.086*</td>
<td>0.270***</td>
<td>0.249***</td>
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<tr>
<td></td>
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<td>(0.089)</td>
<td>(0.053)</td>
<td>(0.055)</td>
<td>(0.061)</td>
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<td>Loss aversion</td>
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<td>0.094</td>
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<td>0.007</td>
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<td>(0.082)</td>
<td>(0.057)</td>
<td>(0.058)</td>
<td>(0.073)</td>
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<tr>
<td>Woman</td>
<td>0.123</td>
<td>0.021</td>
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<td>-1.01*</td>
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<td>(0.062)</td>
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<tr>
<td>Experience</td>
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<td>0.070</td>
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<tr>
<td></td>
<td>(0.104)</td>
<td>(0.077)</td>
<td>(0.105)</td>
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<tr>
<td>Capital gains limit</td>
<td>0.047</td>
<td>0.012</td>
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<td>-0.035</td>
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</tr>
<tr>
<td>(standardized)</td>
<td>(0.064)</td>
<td>(0.048)</td>
<td>(0.047)</td>
<td></td>
<td></td>
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<tr>
<td>Capital losses limit</td>
<td>-0.076</td>
<td>-0.059</td>
<td>0.017</td>
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</tr>
<tr>
<td>(standardized)</td>
<td>(0.066)</td>
<td>(0.048)</td>
<td>(0.046)</td>
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<tr>
<td>Constant</td>
<td>-0.319</td>
<td>-0.158</td>
<td>0.206**</td>
<td>0.181</td>
<td>0.237**</td>
<td>0.339***</td>
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<tr>
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<td>(0.146)</td>
<td>(0.169)</td>
<td>(0.093)</td>
<td>(0.103)</td>
<td>(0.126)</td>
<td>(0.125)</td>
</tr>
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<tr>
<td>R²</td>
<td>0.198</td>
<td>0.229</td>
<td>0.091</td>
<td>0.129</td>
<td>0.187</td>
<td>0.223</td>
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</tbody>
</table>
Appendix A

Calculation of the Net Expected Value

Let $P_{i,T-1}$ be the price of stock $i$ in trial $T-1$, after any price update about the stock. $S_i^T = \text{good}$ indicates stock $i$ is good state in trial $T$ and $S_i^T = \text{bad}$ indicates the opposite.

Let $G_i^T = \Pr(S_i^T = \text{good}|P_i^T, P_i^{T-1}, \ldots, P_i^0)$ be the probability that a Bayesian investor, after observing the price update in trial $t$, would consider stock $i$ as being in the good state in trial $T$. Moreover, let $Z_T$ take the value 1 if the price update in trial $T$ indicates a price increase for the stock and -1 if the price update indicates a price decrease, $\Pr(Z_T|S_i^T = \text{good}) = 0.5 + 0.2Z_T$. If $G_i^T = G_i^{T-1}$, then the price update in period $T$ was not about stock $i$; but if the price update in period $T$ was about stock $i$, then:

\[
G_i^T (G_i^{T-1}, Z_T) = \frac{\Pr(S_i^T = \text{good}|G_i^{T-1}, Z_T)}{\Pr(Z_T)}
\]

\[
= \frac{\Pr(Z_T|S_i^T = \text{good})\Pr(S_i^T = \text{good}|G_i^{T-1})}{\Pr(Z_T)}
\]

\[
= \frac{\Pr(Z_T|G_i^{T-1})\Pr(S_i^T = \text{good}|G_i^{T-1}) + \Pr(Z_T|S_i^T = \text{bad})\Pr(S_i^T = \text{bad}|G_i^{T-1})}{(0.5 + 0.2Z_T)(0.8G_i^{T-1} + 0.2(1-G_i^{T-1})) + (0.5 - 0.2Z_T)(0.2G_i^{T-1} + 0.8(1-G_i^{T-1}))}
\]

At the beginning of the experiment, the state of stock $i$ is randomly assigned and stock price is 100, $G_i^0 = 0.5$ and $P_i^0 = 100$. The optimal strategy for an expected value investor is to sell (if holding) or not repurchase (if not holding) stock $i$ in period $T$ when $G_i^T < 0.5$; and to hold or repurchase it otherwise. This is because the expected price change on the next price update (Net Expected Value) is given by

\[
\text{Net Expected Value}^T = E[\Delta P^{T+1}|G_i^T, P_i^{T+1} \neq P_i^T] - P_i^T = E[\Delta P^{T+1}|G_i^T, \Delta P^{T+1} \neq 0]
\]

\[
= \Pr(S_i^{T+1} = \text{good}|G_i^T) \times [0.3 \times 10 + 0.7 \times (-10)] + \Pr(S_i^{T+1} = \text{bad}|G_i^T) \times [0.3 \times 10 + 0.7 \times (-10)]
\]

\[
= [0.8G_i^T + 0.2(1-G_i^T)] \times 4 + [0.2G_i^T + 0.8(1-G_i^T)] \times (-4)
\]

\[
= 4[0.6G_i^T + 0.2 - 0.8 + 0.6G_i^T] = 2.4[2G_i^T - 1]
\]

A risk neutral subject who follows the optimal strategy will repurchase whenever Net Expected Value is positive ($G_i^T > 0.5$) and will not repurchase (or will sell) whenever Net Expected Value is negative ($G_i^T < 0.5$).
Appendix B

Experimental Instructions

Welcome to our experiment. In this experiment you will be given one unit of stock A, one unit of stock B, one unit of stock C, and 50 experimental currencies. The initial price of each stock is 100 experimental currencies per unit.

There are 30 periods in the experiment. Every period one of the three stocks will be chosen randomly and updated its price by the computer. Period 1 to 6, you will only see the information of stock price updating and cannot trade any stock. Since period 7, you have opportunity to buy or sell the stock that is chosen and updated its price in the computer screen.

Each stock changes price according to the exact same rule. Each stock is either in a good state or in a bad state. In the good state, the stock goes up with 70% chance, and it goes down with 30% chance. In the bad state, the stock goes up with 30% chance, and it goes down with 70% chance. Once it is determined whether the price will go up or down, the size of the change is always random, will either be 5, 10, or 15 experimental currencies. The stock will all randomly start in either the good state or bad state, and after each price update, there is a 20% chance the stock witches state.

For example, if this period stock A is good state, its price will go up with 70% chance, and the amount it goes up by is 5, 10, or 15 with equal chance. At the same time its price will go down with 30% chance, and the amount it goes down by is 5, 10, or 15 with equal chance. In the next period, if stock A is chosen, it is still good state with 80% chance, and it switches to bad state with 20% chance.

<table>
<thead>
<tr>
<th>Stock price changes</th>
<th>Good state</th>
<th>Bad state</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>70%</td>
<td>30%</td>
</tr>
<tr>
<td>–</td>
<td>30%</td>
<td>70%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>State changes</th>
<th>Good state next period</th>
<th>Bad state next period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good state this period</td>
<td>80%</td>
<td>20%</td>
</tr>
<tr>
<td>Bad state this period</td>
<td>20%</td>
<td>80%</td>
</tr>
</tbody>
</table>

Every period only one of the three stocks will be chosen randomly and updated its price, the price of the other two stocks in this period does not change. You can see the chosen stock, its current price, amount of price change, and your available cash; while the state of the stock is not displayed.

Please note:
(1) At the beginning of the entire experiment, you first need to answer two questions: “How much capital gains of a hold stock brings to you, you will sell it” and “How much capital losses of a hold stock brings to you, you will sell it”. Non-binding limits of capital gains and capital losses are possible and you could not adjust limits during the entire experiment.

(2) Each period you have 15 seconds to make a response by pressing the BUY (SELL) or NOT BUY (NOT SELL) button, otherwise the computer will randomly select a response for a subject.

(3) You are only allowed to hold a maximum one unit of each stock, and you cannot hold negative units (no short selling). However, you can carry a negative cash balance by buying a stock for more money than you have, but any negative cash balances will be deducted from your final earnings.

Your earnings at the end of the experiment will be equal to the amount of cash you accrued over the all periods from buying and selling stocks, plus the current price of any stocks that you own. \( \text{Earnings} = \text{cash} + \text{price A}\times(\text{hold A}) + \text{price B}\times(\text{hold B}) + \text{price C}\times(\text{hold C}) \).

Finally, your earnings will be converted using an exchange of 20:1. That means we divide your earnings by 20, and pay you this amount plus the 5 yuan show up fee.

Computer Screens and Examples

For example, if stock C is chosen in period 1, see Panel (a) in Figure S1. Stock C has increased 15 experimental currencies; its current price is 115 experimental currencies; your purchase price is 100 experimental currencies; your available cash is experimental currencies 50. From period 1 to 6, you will see a similar computer screen.

If period 13 the stock A is chosen, stock A has increased 5 experimental currencies; its current price is 105; your purchase price is 100; your available cash is 130. You need to decide whether to sell the stock through entering the button of “Yes” or “No” in 15 seconds, see Panel (b) in Figure S1.

If period 16 stock A is chosen. Stock A has decreased 5; its current price is 110; your available cash is 365. You need to decide whether to buy the stock through entering the button of “Yes” or “No” in 15 seconds, see Panel (c) in Figure S1.

Figure S1. Examples of z-Tree screen in the experiment. For periods 1-6, subject observes a screen like Panel A in which a stock price is updated and are not allowed to trade the stock; he or she can observe the label of chosen stock (stock A, or stock B, or stock C), the updated price and purchase price of the stock, and their available cash.
After period 6, a subject can observe a screen like Panel (b) or Panel (c). If he or she holds the chosen stock in a period, a screen like Panel B is displayed; a subject decides whether to sell it. If a subject does not hold the chosen stock, a screen like Panel (c) is displayed; he or she decides whether to buy it. The screen shown in Panel (b) illustrates a period the stock A is chosen and a subject holds stock A. The screen shown in Panel (c) illustrates a period the stock A is chosen and a subject does not hold stock A. Each period a subject has 15 seconds to make a response by pressing the BUY (SELL) or NOT BUY (NOT SELL) button, otherwise the computer will randomly select a response for a subject.

Panel (a)
Panel (b)

Panel (c)