# EMOTIONS AND COGNITION IN FINANCIAL DECISION-MAKING

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# EMOTIONS AND COGNITION IN FINANCIAL DECISION-MAKING

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EDITORIAL
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# Editorial: Emotions and Cognition in Financial Decision-Making

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**Keywords: emotion, cognition, decision making, behavioral finance, behavioral economics, neuroeconomics**

**Editorial on the Research Topic**

**Emotions and Cognition in Financial Decision-Making**

The relationship between emotions and cognition and their impact upon behavior has moved through several trends, beginning with theory positing that "hot" emotions are simply a by-product of "cold" cognition through to the widely accepted perspective that emotions are an integrative signal within decision-making and that cognitions and emotions influence each other to drive behavior. It is within this integrative perspective that behavioral finance aims to elucidate human factors within the marketplace, and wherein lies this Research Topic. A reliance on theory and methods that ignore or avoid human emotional influences on decision making under uncertainty has been put forward for, at least partial, blame in several significant real world debacles including stock market bubbles and crashes, questionably immoral organizational culture and significant mismanagement of projects leading to significant reputational damage to organizations and in some cases, their complete downfall.

Behavioral finance aims to produce predictive models of human behavior within financial contexts, leading to a step-change in the understanding of human factors in such contexts. To achieve this goal, human factors that play significant roles in financial decision making need to be identified and their impacts on observable behavior measured. Through such effort, researchers can provide information for subsequent modeling and the creation of efficacious psychological interventions, an ambitious challenge given the breadth of human behavior to be considered. This Research Topic brings together a range of modern research using a variety of empirical methods under this one aim.

A key concept within the understanding of human factors in financial decision-making is how humans perceive and represent risk. Risk is ubiquitous within financial decisions (indeed, almost all decisions we make) given that cost-benefit analyses are typically involved which entail some form of estimated risk. Liu et al., in their paper *Influence of the manner of information presentation on risky choice* show that presenting well-defined lotteries either by *alternatives* (presenting each alternative in turn) or by *dimensions* (presenting either the two magnitudes or two probabilities of each choice together) is associated with differences in utilization of expected utility calculations between presentation frames and that this effect is affected by the amount of covert attention to the presentation of information. Wang et al., in their paper *Influence factors for decision-making performance of suicide attempters and suicide ideators: the roles of somatic markers and explicit knowledge* find evidence to suggest that suicide attempters, a relatively less-researched population, use a compensatory choice strategy on the Iowa Gambling Task to improve performance to the level of healthy controls. Another common factor in every-day decision making is the need to wait for outcomes to be experienced. Yang et al. investigate how the detail in which a delay is described or cut into segments affects delay discounting in their paper *Time unpacking effect on inter-temporal decision-making: Does the effect change with choice valance?* They find that time

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unpacking influences tolerance of delay, regardless of whether the unpacking is of positive, neutral or negative valence (for example, receiving a gift, washing hair or attending a funeral, respectively).

Neuroeconomics is the relatively new science building on the integration of economics and psychology within behavioral economics to include methods and understanding from cognitive neuroscience, with the aim of building predictive models of human behavior considering the structure and function of the human brain, in other words, building models fitted to how the brain works. Hinvest et al. investigate the relationship between anticipatory emotions and trading performance using a complex trading simulation in their paper *Do emotions benefit investment decisions? Anticipatory emotions and investment decisions in non-professional investors.* The Authors measure galvanic skin response to find that emotions integrated into decision-making are neither wholly beneficial nor detrimental to trading performance but that the relationship is dependent on the behavior of the stock market. Gao et al. in their paper *More negative FRN from stopping searches too later that too early? An ERP study* measure Feedback Related Negativity (FRN). They report that this neural marker of feedback-driven attentional signaling is greater when a participant spends too long on information search vs. when they spend too little time, positing that this is indicative of the level of experienced regret. Suo et al. measure the carry-over effects of anger and sadness on inter-temporal choice in their paper *The differential effects of anger and sadness on intertemporal choice: an ERP study*. The Authors find that facial anger primes affect discounting behavior and peak of particular event-related potentials (ERPs), subsequently suggesting psychological factors underlying the changes. Guttman et al. take a structural approach to the brain in their paper *Age influences loss aversion through effects on cortical thickness*, finding that atrophy of the posterior cingulate cortex after middle adulthood is associated with decreases in loss aversion. Yang et al. mix neuroeconomics with a popular contemporary topic, that of social investing, in their paper *Are people altruistic when making socially responsible investments? Evidence from a tDCS study*. Via the use of transcranial direct current stimulation (tDCS), the Authors modulated the activity with the right temporo-parietal junction, an area previously associated with altruism and social behavior, and find that this influences willingness to invest in a more socially-minded way.

Finally, Bossaerts provides an intriguing review entitled *How neurobiology elucidates the role of emotions in financial decision-making*. In the review, Bossaerts uses a recently published paper with a relatively small sample size as an example to elucidate misconceptions around the integration of emotion into risk-based decision-making, highlighting the value that cognitive neuroscience can bring to traditional economic models of behavior.

This Research Topic beings together a range of methods and perspectives to elucidate human factors in financial decision-making. This is befitting to the field which crosses many disciplines and engages a wide range of academic and practitioner stakeholders. In traditional financial research, the outcome of the decision-making process is focal. While some classical theory incorporates a role for emotion, the contributions in this Research Topic illustrate the interaction between emotion and cognition. Both emotion and cognition should be recognized as fundamental components and dual forces in understanding financial decision-making.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Time Unpacking Effect on Intertemporal Decision-Making: Does the Effect Change With Choice Valence?

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People often feel that a period of time becomes longer when it is described in more detail or cut into more segments, which is known as the time unpacking effect. The current study aims to unveil how time unpacking manipulation impacts intertemporal decision making and whether the gain-loss valence of choices moderates such impacts. We recruited 87 college students (54 female) and randomly assigned them to the experimental conditions to complete a series of intertemporal choice tasks. The subjective values of the delayed choices were calculated for each participant and then analyzed. The results showed that participants perceived longer time delays and higher subjective values on the delayed gains (but not losses) in the time unpacking conditions than in the time packing conditions. These results suggest that time unpacking manipulation not only impacts time perception but also other factors, which in turn, influence the valuation of delayed outcomes and thereby intertemporal choices. The results are discussed in comparison to previous studies to highlight the complexity of the mechanism underlying the effect of time unpacking on intertemporal decision making.

**Keywords: intertemporal choice, temporal discounting, time unpacking effect, emotional valence, time perception**

## INTRODUCTION

Intertemporal decision-making refers to the process of weighing and choosing outcomes that occur at different points in time, such as a short-term vs. a long-term benefit, writing a manuscript today vs. next week (Frederick et al., 2002). As a critical aspect of intertemporal choice, time significantly influences the decisions people make. The time unpacking effect, a relatively newly identified phenomenon, shows that framing time in an unpacking manner (e.g., describing more events and remarks on the timeline or cutting a time interval into a larger number of small segments) extends the length of time interval people perceive. It is thus reasonable to speculate that the manipulation of unpacking time may influence people's time perception and thereby their intertemporal decision-making. The current study aims to examine this speculation, as well as to investigate whether the emotional states of decision-makers and the gain-loss valence of choices moderate the effect of time unpacking on intertemporal decision making. Addressing these issues could contribute to a better understanding of the framing effect in intertemporal decision-making.

## Intertemporal Decision-Making

Intertemporal decision-making has been widely researched in multiple disciplines, such as economics, neuroscience, and psychology. A commonly used research paradigm is to let participants choose between a smaller but sooner (SS) and a larger but later (LL) outcome, for example, between "getting/paying $100 now" and "getting/paying $200 after 6 months." Using such or similar paradigms, research has frequently shown a temporal preference: people often prefer SS over LL gains and LL over SS losses (Frederick et al., 2002).

Such a temporal preference is often explained by the mental process of temporal discounting (also known as time discounting and delay discounting), which means that the utility or subjective value of an outcome is discounted when delayed (Green and Myerson, 2004). By temporal discounting, a person may perceive that the value of an LL gain (or loss) is smaller than that of an SS gain (or loss), and thus prefer the SS gain (or the LL loss; Green and Myerson, 2004). A series of mathematics models have been proposed to sketch the relationship between the objective and subjective values of future outcomes (e.g., Frederick et al., 2002), such as the widely cited exponential discounting model $V = Ae^{-\delta D}$ (Samuelson, 1937) and hyperbolic discounting model $V = A/(1 + kD)$ (Ainslie, 1975). In these models, $A$ is the amount (i.e., objective value), $V$ is the subjective value, $D$ is the time delay, and $\delta$ and $k$ are the discount rate of the delayed outcome. According to these models, the subjective value of a given future outcome is determined by the time delay $D$ and discount rate $\delta$ or $k$: A longer time delay and a larger discount rate result in a smaller subjective value (i.e., a larger degree of discounting). Discount rate can be increased by multiple factors, such as longer perceived time intervals, higher perceived time cost, and stronger sensitivity to and psychological impact of the sooner outcomes (Frederick et al., 2002). To clarify, *discount rate* ($\delta$ or $k$) is different from the term *degree or extent of temporal discounting* used in the current and some other studies (Frederick et al., 2002; Green and Myerson, 2004). By the latter, we refer to the difference in the subjective value of the SS and the LL choices, which is a function of discount rate and time delay.

## The Time Unpacking Effect on Intertemporal Decision-Making

Since intertemporal decision-making involves evaluating and comparing choices at different time points, the perception and estimation of time interval is a critical factor that affects a decision maker's choices. Studies (Liu and Sun, 2016; Kim and Zauberman, 2019) have found that changing individuals' time-interval perception can alter their intertemporal choices.

One way to change time-interval perception is to frame it in an unpacking manner, which has been called the time unpacking effect (Kruger and Evans, 2004; Liu and Sun, 2016). To put it in a colloquial language, the unpacking effect means that the whole is less than the sum of its parts (Van Boven and Epley, 2003). It has been broadly investigated under the framework of Support Theory (Tversky and Koehler, 1994). The theory asserts that human judgments of probabilities are attached not to events but to the descriptions of events. The perceived probability of an event (e.g., death from an unnatural death) increases when the event is descriptively unpacked by giving more examples or details (e.g., death from car accidents, homicide, suicide, and fires). Similar effects have been detected for other quantitative judgments, such as the severity of an event's consequence (Van Boven and Epley, 2003).

The unpacking effect has also been found for time perception (Kruger and Evans, 2004; Liu and Sun, 2016). For example, Kruger and Evans (2004) found that a day was perceived to be longer when specific plans for different timepoints of the day were described than when such details were not described. Liu and Sun (2016) found that a 3-month delay was perceived to be longer when it was described in an unpacking manner ("after the first, second, and then the third month") than when it was described in a packing manner ("after 3 months").

The findings of some other studies (Van Boven and Epley, 2003; Tsai and Zhao, 2011) also hint at the existence of the time unpacking effect. In daily life, people often use distinctive, memorable events to mark a point in time or segment a period of time (e.g., "the day when we first met," "from the day I graduated till the day I get a tenure-track job"). People may feel that time passes faster when they experience such events more intensively during a time period. However, when looking back afterward, they tend to perceive this time period to be longer (Bruss and Rüschendorf, 2010). Even without those landmark events, a time period still could be perceived to be longer when it is divided into a larger number of segments. For example, people tend to feel a 30-month interval becomes longer when it is divided into 10 3-month intervals (Kim and Zauberman, 2019).

To our knowledge, few studies (Liu and Sun, 2016) have examined the time unpacking effect on intertemporal decision making. Liu and Sun (2016) found that participants in the time-unpacking conditions discounted the delayed rewards to larger degrees, thereby showing a stronger preference for immediate over delayed rewards relative to those participants in the time-packing conditions. It is unknown yet whether the time unpacking manipulation interacts with other factors important to intertemporal decision-making, such as the decision-makers' emotional states and the gain/loss valence of choices.

## The Effect of Emotional State

As reviewed by Herman et al. (2018), a pleasant mood could generally lower discount rate and increase patience (Liu et al., 2013), and an unpleasant mood could increase the discount rate and lead to more impulsive behavior (Augustine and Larsen, 2011; Koff and Lucas, 2011). Emotional state might moderate the effect of time unpacking on intertemporal decision-making through two approaches. On the one hand, emotional state could influence the perception of time interval. Individuals tend to perceive that time is slowing down and time interval is getting longer when they are in an unpleasant (vs. pleasant) state (Guan et al., 2015) and in a high-arousal (vs. low-arousal) state (Droit-Volet et al., 2013). As a result, they are more likely to overestimate the length of time intervals, leading to a stronger preference for SS gains (Kim and Zauberman, 2019).

On the other hand, emotional state could influence the discount rate during decision-making, which is not necessarily associated with time-interval perception. For example, by imagining future emotional events with different valence, empirical studies (Calluso et al., 2019) showed that unpleasant (vs. pleasant) and high-arousal (vs. low-arousal) emotional states tended to make individuals behave more impulsively and discount delayed gains to larger degrees. Moreover, with six experiments, Pyone and Isen (2011) found positive emotions promoted cognitive flexibility, cultivated a higher level of thinking and a more future-oriented view of time, and thereby facilitated participants' preference for LL gains. Thus, it is reasonable to speculate that emotional state may moderate the time unpacking effect on intertemporal decision-making. The current study manipulated participants' emotional states by instructing them to imagine future events toned with various emotional valence.

## The Effect of Choices' Gain-Loss Valence

A myriad of research has demonstrated the essential role of gain-loss valence in decision making (Kahneman and Tversky, 1979). Intertemporal decision-making situations involving losses are as common as those involving gains in daily life, but much less attention has been paid to the former than to the latter in research. The existing studies (e.g., Frederick et al., 2002) have shown that individuals not only discount the subjective value of delayed gains but also that of delayed losses. Namely, a later loss is perceived to be less aversive than a sooner loss of the same amount. The discounting of losses and gains can be fit by similar models (Estle et al., 2006), and the discount rates are usually lower for losses than for gains [known as the sign effect or gain-loss asymmetry (Frederick et al., 2002)]. It may be because losses are more psychologically impactful due to humans' stronger tendency of loss aversion (Kahneman and Tversky, 1979), and thus are more resistant to mental discounting (Frederick et al., 2002). Thus, choice valence may moderate the effect of time unpacking on intertemporal decision-making by affecting the discount rate. Moreover, choice valence may also affect the perception of time interval (e.g., Bilgin and LeBoeuf, 2010). For instance, with a series of experiments, Bilgin and LeBoeuf (2010) showed that individuals tend to perceive shorter time intervals for delayed losses than for delayed gains.

In summary, the time unpacking manipulation may change individuals' time-interval perception, thereby altering their perceived value of delayed gains/losses and eventually their choices in intertemporal decision-making tasks. Though yet to be examined, it is possible that the effect of time unpacking on intertemporal choices may be moderated by both decision makers' emotional states and choices' gain-loss valence.

## The Current Study

The current study aimed to examine the effect of time unpacking on intertemporal choice, as well as how this effect is moderated by emotional state and choice valence. According to the literature discussed above, we proposed two hypotheses.

> *H1*: Time unpacking manipulation can influence intertemporal choices by prolonging perceived time intervals and thereby downscaling the subjective value of delayed choices (i.e., increasing the degree of temporal discounting).
>
> *H2*: Emotional state and choice valence can moderate the effect of time unpacking on time perception and the subjective value of delayed choices. An unpleasant mood will reduce the perceived length of time and thus mitigate the time unpacking effect, while a pleasant mood will strengthen this effect.

# MATERIALS AND METHODS

## Participants

A sample of 87 Chinese college students (54 female; aged between 18 and 27 years, $M$ = 21.07, $SD$ = 1.59) were recruited to participate in the current study through posters. Three participants were excluded from the analysis due to invalid responses. According to the power analysis by G*Power version 3.1 (Faul et al., 2009), this sample size allowed us to detect an effect $f$ = 0.14 (equivalent to $\eta^2_p$ = 0.020) in our design with a power of $1-\beta$ = 0.80 at a level of $\alpha$ = 0.05, which was between a small ($f$ = 0.10) and a medium ($f$ = 0.25) effect sizes (Cohen, 1977). Participants gave informed consent before the experiment and were debriefed with the research purpose after the experiment. By completing the experiment, each participant received RMB 10 yuan (around 1.44 US dollars) as compensation. The study received ethical approval from the Ethics Committee of the Faculty of Education at Hubei University.

## Tasks and Measurement

### Induction and Measurement of Emotion

Emotional states were induced by an episodic-thinking (ET) task. Research has found that imagining pleasant events (the pleasant ET condition) can evoke pleasant emotions, while imagining unpleasant events (the unpleasant ET condition) can trigger unpleasant emotions (Wang et al., 2012). Specifically, we presented each participant with one of three event lists: pleasant-event list (winning a scholarship, holding a wedding, receiving a gift, attending a wedding with good friends, and passing an exam), neutral-event list (washing clothes, washing hair, brushing teeth, washing feet, and washing face), and unpleasant-event list (fighting with a good friend, food poisoning, attending a relative's funeral, arguing with parents, and a car accident). Participants were free to choose one of the five events on the list and then imagined themselves experiencing this event at a moment in the future. It has been shown that these events are often perceived as common and personally relevant by Chinese young adults (Liu et al., 2013). After the ET task, participants self-reported whether they had imagined the event as instructed (1 = *no*; 2 = *yes*); they also rated the vividness of imagination (from 1 = *not vivid at all* to 7 = *very vivid*), emotional valence of the event (from 1 = *very unpleasant* to 7 = *very pleasant*), emotional arousal of the event (from 1 = *very low* to 7 = very high), and personal relevance of the event (from 1 = *totally irrelevant* to 7 = *totally relevant*).

The Chinese version (Qiu et al., 2008) of the Positive and Negative Affect Schedule (PANAS) was used to measure participants' emotions before the ET (i.e., pretest/baseline emotions) and at the end of the whole experiment (i.e., posttest emotion). The scale consisted of nine words describing pleasant emotions (i.e., active, energetic, happy, elated, excited, proud, joyful, vigorous, and grateful) and nine words for unpleasant emotions (i.e., shameful, sad, scared, nervous, terrified, guilty, irritable, trembled, and angry). For each emotion, participants rated the extent to which they were experiencing it at that moment on a five-point Likert scale (from 1 = *not at all* to 5 = *extremely*). Cronbach's α of the pre- and post-test was 0.90 and 0.96 for the positive affect subscale, and 0.92 and 0.95 for the negative affect subscale.

### Manipulation and Measurement of Time Perception

Following the previous studies (Liu and Sun, 2016), time perception for the delay was altered through time-unpacking manipulation. In the time-unpacking condition, the LL option in the intertemporal choice tasks was "From now on, after passing through the 1st, 2nd, 3rd, 4th, 5th, and 6th month, get (or pay) 1,000 yuan." In the time-packing condition, the LL option was "Get (or pay) 1,000 yuan after 6 months." After the choice tasks, participants reported their perceived time delay (i.e., subjective delay) of the LL option by rating on a continuous scale ranging between 1 and 100 (Liu and Sun, 2016).

### Intertemporal Choice Task

Each participant completed four blocks of intertemporal choice-making task, each consisting of 19 trials. The four blocks corresponded to the four "time unpacking × choice valence" conditions (i.e., the time-packing gain condition, time-packing loss condition, time-unpacking gain condition, and time-unpacking loss condition). Similar to previous studies (Rachlin et al., 1991), in each trial participants chose between two options: An SS option "Get (or pay) $x$ yuan now" and an LL option "Get (or pay) 1,000 yuan after 6 months" (time-packing) or "From now on, after passing through the 1st, 2nd, 3rd, 4th, 5th, and 6th month, get (or pay) 1,000 yuan" (time-unpacking). The amount of gain (or loss) in the LL option remained the same, while that in the SS option (i.e., $x$) increased from 50 yuan to 950 yuan in order with a step of 50 across the 19 trials within a block.

## Experimental Design and Procedures

The experiment adopted a mixed 3 (ET: pleasant, neutral, or unpleasant; between-subject) × 2 (time unpacking: yes or no; within-subject) × 2 (choice valence: gain or loss; within-subject) design. Participants were randomly assigned to the pleasant ($n$ = 31), unpleasant ($n$ = 30), and neutral ET conditions ($n$ = 26) to complete the experiment run by E-prime 2.0 on computer.

As displayed in **Figure 1**, participants first completed the Chinese version of the PANAS (Qiu et al., 2008), which measured their current emotional state (pretest emotions). Afterward, they were instructed to choose an event from one of the event lists (the pleasant, neutral, or unpleasant event list) and imagine it vividly for 2 min (i.e., the ET task), and then they answered several questions checking their engagement in the ET task.

Next, participants completed four blocks of intertemporal choice task, each corresponding to a time packing × choice valence condition (i.e., the time-packing gain condition, time-packing loss condition, time-unpacking gain condition, or time-unpacking loss condition). A fixed sequence among the blocks was adopted, that is, time-packing gain, time-packing loss, time-unpacking gain, and time-unpacking loss. Each block consisted of 19 trials and all trials used a fixed sequence from small to large. In each trial, participants watched a screen with a cross at its center lasting for 800 ms, followed by a blank screen lasting for 500 ms, and then an intertemporal choice task. Participants were instructed to make a choice by pressing certain keys on the keyboard without a time limit. After finishing all 19 trials of choice tasks in each block, participants rated their perceived time delay for the LL option (which was the same for all trials within a block) in the block.

At the end of the experiment, participants completed the Chinese version of the PANAS again that measured their current emotional states (posttest emotions).

## Analytic Strategies

For each experimental condition of each participant, the subjective value of the LL option equaled to the mean value of the last LL option and the first SS option when a participant shifted his or her choice from the LL to SS options in the ordered sequence of intertemporal choice-making trials. For example, if the participant choose the LL option for the fourth trial (SS = 200 yuan, LL = 1,000 yuan) but the SS option for the fifth trial (SS = 250 yuan, LL = 1,000 yuan) in a task block, then the subjective value of the LL option (i.e., the delayed 1,000 yuan) was (200 + 250)/2 = 225 yuan.

To test our hypotheses, the subjective time delays and subjective values of the LL options were submitted to the *Afex* (Singmann et al., 2020) and *emmeans* (Lenth, 2021) packages on R version 3.6.0 (R Core Team, 2020) for a mixed design repeated measures 3 (ET: pleasant, neutral, or unpleasant; between-subject) × 2 (time unpacking: yes vs. no; within-subject) × 2 (choice valence: gain vs. loss; within-subject) ANOVA. In addition, the validity of the emotion manipulation was also checked.

# RESULTS

## Demographics

The demographic information of the three ET conditions is displayed in **Table 1**. ANOVAs showed no significant differences

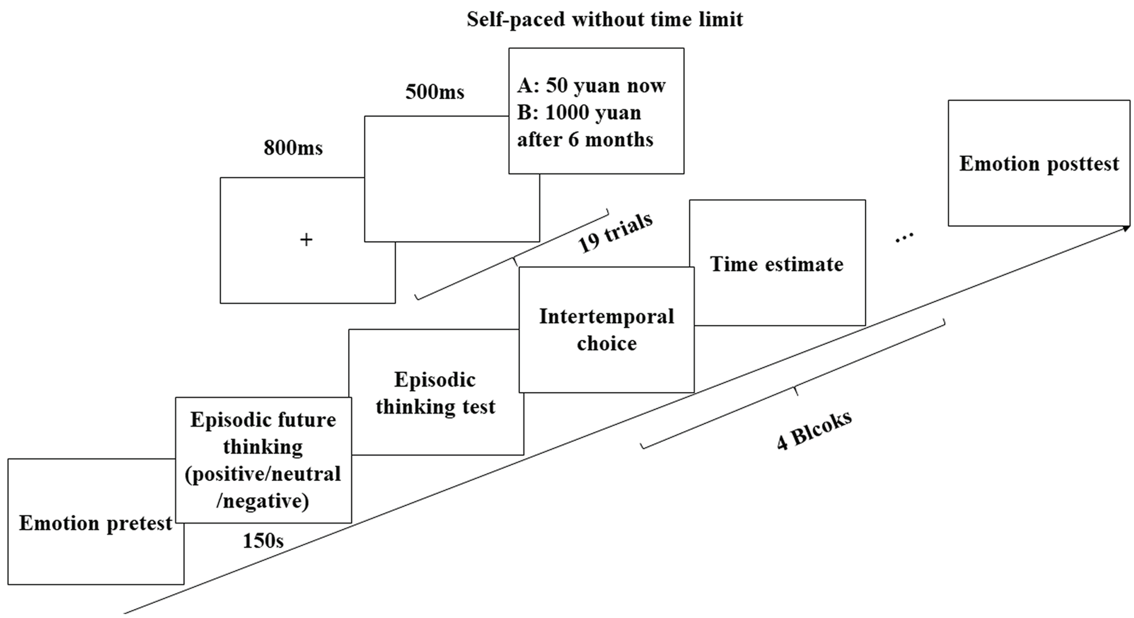


**FIGURE 1** | A flow diagram showing the procedures of the experiment.

**TABLE 1** | Sample characteristics.

| Demographic variables | Pleasant condition | Neutral condition | Unpleasant condition |
|---|---|---|---|
| Gender (m:f) | 11:20 | 8:18 | 14:16 |
| Age (year) | 21.29 ± 1.64 | 21.23 ± 1.73 | 20.7 ± 1.39 |
| Education (year) | 15.23 ± 0.88 | 15.42 ± 1.3 | 15 ± 1.02 |
| **Major** | | | |
| Engineering | 2 | 5 | 4 |
| Science | 13 | 13 | 14 |
| Literature | 14 | 7 | 12 |
| Art | 2 | 1 | 0 |
| Monthly consumption (RMB yuan) | 1454.84 ± 494.53 | 1653.85 ± 936.90 | 1636.67 ± 862.83 |
| Urgency of needing money | 2.65 ± 1.40 | 2.85 ± 1.29 | 3.10 ± 1.30 |

in age, $F(2, 84) = 1.25$, $p = 0.29$, $\eta^2_p = 0.03$, years of schooling, $F(2, 84) = 1.10$, $p = 0.34$, $\eta^2_p = 0.03$, monthly consumption level, $F(2, 84) = 0.60$, $p = 0.55$, $\eta^2_p = 0.01$, or urgency of needing money, $F(2, 84) = 0.89$, $p = 0.41$, $\eta^2_p = 0.02$, across the three conditions. Chi-square tests showed no significant differences among the three conditions in gender ratio, $\chi^2(2) = 1.60$, $p = 0.40$, or major of study, $\chi^2(6) = 5.2$, $p = 0.50$.

## Check of Emotion Manipulation

All participants reported that they had imagined the event in the ET task as instructed. Participants' ratings on the features of the imagined events are displayed in **Table 2**. ANOVAs showed no significant differences in vividness, $F(2, 84) = 1.18$, $p = 0.31$, $\eta^2_p = 0.03$, or personal relevance, $F(2, 86) = 1.02$, $p = 0.37$, $\eta^2_p = 0.02$, but significant differences in emotional valence, $F(2, 86) = 134.33$, $p < 0.001$, $\eta^2_p = 0.76$, and arousal of the event, $F(2, 86) = 15.24$, $p < 0.001$, $\eta^2_p = 0.27$. *Post hoc* tests revealed that emotional valence was the highest in the pleasant and lowest in the unpleasant ET condition ($ps < 0.001$). Arousal was higher in the pleasant and unpleasant conditions than in the neutral condition ($ps < 0.001$). The results indicated that participants were engaged in the ET task as anticipated.

To test if the ET task induced specific emotions in participants, repeated measures 3 (ET: pleasant, neutral, or unpleasant; between-subject) × 2 (timepoint: pretest vs. posttest; within-subject) ANOVAs on participants' pleasant and unpleasant emotions (measured by the Chinese version of the PANAS) were performed. For pleasant emotions, there was significant main effects of timepoint, $F(1, 84) = 29.68$, $p < 0.001$, $\eta^2_p = 0.26$, and ET condition, $F(2, 84) = 4.50$, $p = 0.014$, $\eta^2_p = 0.10$, as well as a significant ET × timepoint interaction, $F(2, 84) = 4.69$, $p = 0.012$, $\eta^2_p = 0.10$. Simple effect analysis revealed that, at the posttest than at the pretest, participants' pleasant emotions were slightly higher in the pleasant ET condition, $F(1, 84) = 3.45$, $p = 0.067$, $\eta^2_p = 0.04$, slightly higher in the neutral ET condition, $F(1, 84) = 3.75$, $p = 0.056$, $\eta^2_p = 0.04$, and lower in the unpleasant ET condition, $F(1, 84) = 32.71$, $p < 0.001$, $\eta^2_p = 0.28$. For unpleasant emotions, the results showed a significant main effect of timepoint (i.e., less unpleasant at the posttest than the pretest), $F(1, 84) = 16.651$, $p < 0.001$, $\eta^2_p = 0.165$, while the main effect of the ET condition, $F(2, 84) = 0.509$, $p = 0.603$, $\eta^2_p = 0.012$, and the ET × timepoint interaction, $F(2, 84) = 2.211$, $p = 0.116$, $\eta^2_p = 0.050$, were non-significant.

Contradicting our expectation, after the ET task, the pleasant emotions did not increase in the pleasant-ET condition (although they decreased in the unpleasant-ET condition), and the unpleasant emotions decreased in all three ET conditions. These results show that imagining future events did not effectively induce emotions. However, we still included the variable ET

**TABLE 2 |** Results of episodic thinking (ET) in different conditions (*M* ± *SD*).

| Features | Pleasant condition | Neutral condition | Unpleasant condition |
|---|---|---|---|
| Vividness | 5.16 ± 1.27 | 4.81 ± 1.27 | 4.67 ± 1.35 |
| Event valence | 5.74 ± 0.96 | 4.38 ± 0.75 | 2.23 ± 0.77 |
| Event arousal | 5.16 ± 1.04 | 3.73 ± 0.96 | 4.83 ± 1.02 |
| Relevance | 6.23 ± 0.96 | 5.88 ± 0.95 | 6.07 ± 0.78 |
| Pretest PA | 28.90 ± 4.35 | 25.12 ± 6.40 | 28.06 ± 6.02 |
| Pretest NA | 17.32 ± 6.58 | 17.77 ± 6.07 | 17.03 ± 7.07 |
| Posttest PA | 26.74 ± 7.42 | 22.65 ± 7.28 | 21.30 ± 5.57 |
| Posttest NA | 13.19 ± 4.66 | 14.00 ± 5.86 | 16.20 ± 6.74 |

*PA, positive affect; NA, negative affect.*

**TABLE 3 |** Subjective values of delayed choices in different conditions (*M* ± *SD*).

| | Packing | Unpacking |
|---|---|---|
| Gain | 648 ± 295 | 695 ± 241 |
| Loss | 445 ± 358 | 423 ± 337 |

(pleasant, neutral, or unpleasant) in the follow-up analyses to control for the potential impacts of emotion manipulation on the outcome variables of interest.

## Effects on Time Perception

The 3 (ET: pleasant, neutral, or unpleasant; between-subject) × 2 (time unpacking: yes vs. no; within-subject) × 2 (choice valence: gain vs. loss; within-subject) ANOVA on subjective time showed that only the main effect of time unpacking was significant, $F(1, 81) = 7.76$, $p = 0.007$, $\eta^2_p = 0.09$, 95% CI of $\eta^2_p$ = (0.014, 0.193). The subjective time in the time packing condition ($M = 47.8$) was significantly shorter than that in the time unpacking condition ($M = 52.5$), indicating that the time-unpacking operation effectively lengthened the subjective time. Choice valence and emotional manipulation did not moderate the effect of time unpacking on time perception, as indicated by the non-significance of interactions between time unpacking and choice valence and between time unpacking and ET ($ps > 0.10$). The results were consistent with our hypothesis H1.

## Effects on the Subjective Values of Delayed Choices

The 3 (ET: pleasant, neutral, or unpleasant; between-subject) × 2 (time unpacking: yes vs. no; within-subject) × 2 (choice valence: gain vs. loss; within-subject) ANOVA on the subjective value showed a significant main effect of choice valence (the gain conditions > the loss conditions), $F(1, 81) = 31.37$, $p < 0.001$, $\eta^2_p = 0.279$, 95% $\eta^2_p$ CI = (0.147, 0.396) and a non-significant main effect of time unpacking manipulation, $F(1, 81) = 0.42$, $p = 0.52$, $\eta^2_p = 0.005$, 95% CI of $\eta^2_p$ = (0, 0.059). The interaction effect of time unpacking × choice valence was significant, $F(1, 81) = 4.432$, $p = 0.038$, $\eta^2_p = 0.052$, 95% CI of $\eta^2_p$ = (0.001, 0.146). As shown in **Figure 2**, simple effects tests for the time unpacking × choice valence interaction revealed that the effect of time unpacking was significant only for gains, $F(1, 81) = 5.133$, $p < 0.026$, $\eta^2_p = 0.06$, 95% CI of $\eta^2_p$ = (0.004, 0.157), partially supporting our hypothesis H2 (**Table 3**).

# DISCUSSION

With an experimental design, the current study found that time unpacking manipulation lengthened the perceived time delay during intertemporal decision-making, regardless of the manipulation of decision-makers' emotional states, and the gain-loss valence of choices. The time unpacking manipulation also impacted the valuation of the delayed choices: participants discounted the delayed gains (but not losses) less (and thus perceived more values from the delayed gains) when the delay was unpacked than when the delay was not unpacked. The results support H1 and partially support H2.

Replicating the time unpacking effect (e.g., Kruger and Evans, 2004; Liu and Sun, 2016), the current study showed that describing a time interval as a sequence of smaller steps prolonged the length of the interval participants perceived. This effect was robust and not moderated by choice valence, which has been frequently found to impact time perception (e.g., Bilgin and LeBoeuf, 2010; Droit-Volet et al., 2013). Tversky and Koehler (1994) suggested that the time unpacking effect is due to attentional bias. Tse et al. (2004) examined the relationship between attention and temporal distance perception of novel stimuli. They found that subjects with both visual and auditory stimuli tended to judge the presentation time of novel stimuli as being longer than that of standard stimuli. Similarly, temporal decomposition descriptions are uncommon to subjects and therefore its occurrence can overestimate temporal distance (Liu and Sun, 2016).

Contrary to our expectation and previous studies (e.g., Liu and Sun, 2016), time unpacking manipulation did not decrease, but increase the subjective value of delayed gains. In other words, time unpacking manipulation increased participants' perceived time length but decreased their degrees of temporal discounting. Typically, the degree of temporal discounting for a delayed outcome should increase when the perceived time delay prolongs (Kim and Zauberman, 2019). These results suggest that time unpacking manipulation not only impacts time perception but also some other factors, which, in turn, influence the valuation of delayed outcomes and thereby intertemporal choices. Future studies are needed to further explore what these factors could be.

The sense of control over the delayed outcome could be one of these other factors mentioned above. Support theory claims that the probability of a multifaceted category increases and becomes more supportive when the category is unpacked into its components (Tversky and Koehler, 1994). When a period of time is decomposed into several shorter periods, the degree of belief in the longer time perception of this period will be increased. According to the construal level theory (Trope and Liberman, 2003), explicit components are more convincing and can dominate distant behavioral though they have lower construal level (Eyal et al., 2004; Herzog et al., 2007). Therefore, a delayed gain full of explicit components under a time unpacking condition reminds people of possibilities that would not have been considered otherwise,

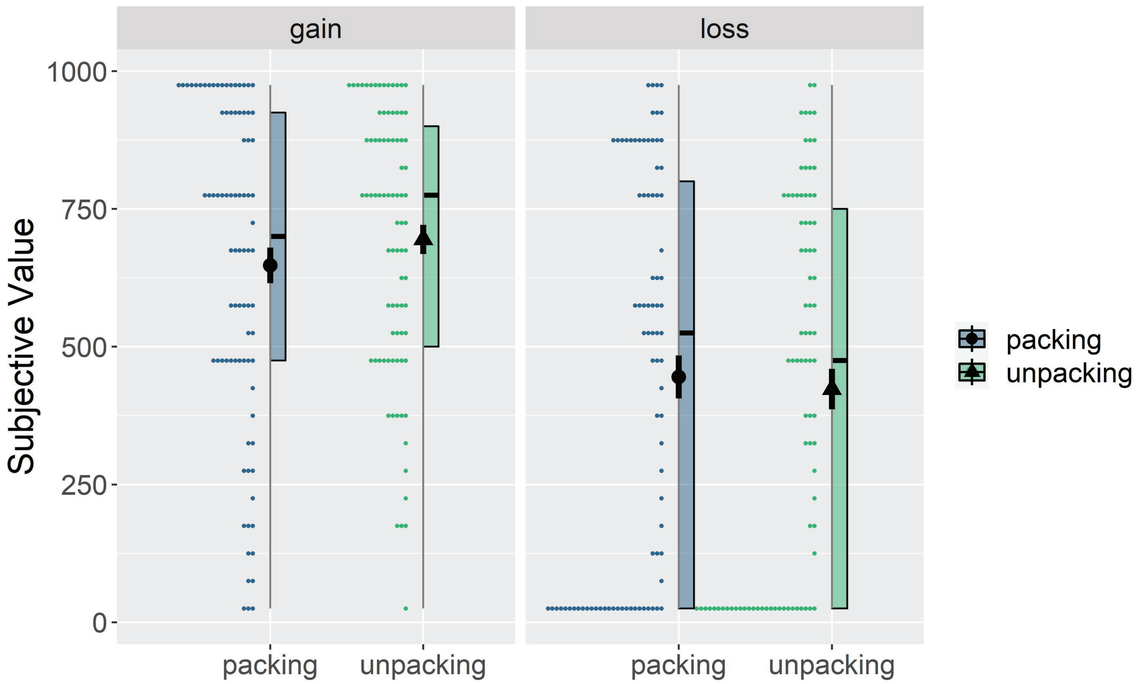


**FIGURE 2** | The interaction effect of time unpacking (packing vs. unpacking) and choice valence (gain vs. loss) on the subjective values of delayed choices. The points in the figure represent the results of each trial. The line is the range of dependent variables. The colored rectangles represent the 25, 50, and 75% quartiles, respectively, and the black dots and line segments represent the mean and SE.

resulting in a lower discount rate. This could be the reason why participants discounted the delayed gains to lower degrees in the unpacking than the packing condition even though the time unpacking condition increased participants' perceived length of delay.

With regard to losses, the time unpacking effect on intertemporal choice was not found. It could be that losses tend to be more psychologically impactful than gains (e.g., Kahneman and Tversky, 1979). According to the endowment effect (Thaler, 1980), people endow the properties they own with high value and are highly averse to losses of the properties. People's strong loss aversion may make them focus more on the value of losses and overlook other information such as time. In line with this speculation, previous studies (e.g., Frederick et al., 2002) have shown that the delay discounting effect is usually smaller for losses than for gains.

Out of our expectation, the emotion-manipulation task (i.e., asking participants to imagine future events) did not effectively induce specific emotional states, although it has been frequently adopted in previous studies (Wang et al., 2014; Calluso et al., 2019; Wang and He, 2019). One of the possible reasons was that the interval between the pretest and posttest of emotional states might have been too long for the manipulation effects to be sustained throughout our study.

## LIMITATIONS AND CONCLUSION

One limitation of the current study was that we only included a single time delay (i.e., a total of 6 months for both the time packing and unpacking conditions) and a fixed magnitude (RMB 1,000 yuan) for the delayed choices. Both the magnitudes and time delays of choices could have modulated temporal discounting (e.g., Frederick et al., 2002). Future studies need to take these factors into account to give a full picture of the time unpacking effect and its interaction with emotion and choice valence. The second limitation was that in this study, titration was used to measure subjective value, and titration was measured in an increasing order, which had an order effect. Moreover, the order between groups was fixed which may have produced a sequence effect. The third limitation was that emotional states were not successfully manipulated. More effective methods should be adopted to manipulate emotional states in future studies.

Despite these limitations, the current study provides supportive evidence for the relatively newly identified time unpacking effect. Namely, time unpacking prolongs the perceived length of time durations. Contradicting some previous studies, the current study showed smaller degrees of temporal discounting in the time-unpacking condition as compared to the time-packing condition, suggesting that time unpacking may influence temporal discounting by impacting multiple factors (but not only time perception). The current study also showed that the effect of time unpacking on temporal discounting could be moderated by contextual factors such as the gain-loss valence of choices. Taken together, these results highlight the complexity of the time unpacking effect on intertemporal decision-making and the need for more research on such an effect.

## DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://osf.io/48bx5/.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of the Faculty of Education in Hubei University. The patients/participants provided their written informed consent to participate in this study. Informed consent was obtained from all individual adult participants included in the study.

## AUTHOR CONTRIBUTIONS

QY analyzed the data and wrote the draft. XG and JX participated in paper writing. SY developed research question and designed the study. All authors contributed to the article and approved the submitted version.

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# The Differential Effects of Anger and Sadness on Intertemporal Choice: An ERP Study

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Previous research has taken a valence-based approach to examine the carryover effects of incidental emotions on intertemporal choices. However, recent studies have begun to explore the effects of specific emotions on intertemporal choices. In this study, we investigated how anger and sadness influenced intertemporal choices using event-related potentials (ERPs). Behavioral results showed that, compared with neutral prime, anger prime was associated with more preference for delayed rewards, whereas sad prime did not change individuals' choice preference. Specifically, anger prime yielded a shorter response time than sad prime for the difficult-to-select choices. ERP results found that, compared with neutral and sad primes, anger prime elicited larger P1 in the fronto-central and parietal areas, larger P2 in the fronto-central area, and larger P3 in the parietal area during the evaluation stage. These findings suggest that there are differential carryover effects of anger and sadness on intertemporal choice. This study provides enlightenment on the significance of understanding how incidental emotions affect individuals' intertemporal choices.

**Keywords: anger, sadness, emotion, intertemporal choice, ERP**

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## INTRODUCTION

Intertemporal choices require people to trade-off between costs and benefits that occur at different points in time (e.g., would you prefer $20 today or $40 in 30 days?) (Frederick et al., 2002). Decisions about investments, spending, savings, mortgages, relationships, education, and diet all involve intertemporal trade-offs. These decisions not only affect an individual's health, wealth, and overall happiness, but also decide the economic prosperity of nations (Frederick et al., 2002). Although intertemporal choices are important and ever-present, people often make choices in a certain emotional state. Research on the influence of emotions on decision-making is based on two perspectives (Lerner et al., 2015). One is the influence of emotions induced by the characteristics of decision-making events (i.e., integral emotion) on decision-making behavior, and the other is the influence of emotions that are not directly related to decision-making events (i.e., incidental emotion) on decision-making behavior. Increasing studies have shown that incidental emotions, which are carried over from one situation to another, influence intertemporal choices that are unrelated to that incidental emotion (Loewenstein, 2000; Raeva et al., 2010; Lerner et al., 2015; Lempert and Phelps, 2016).

Most research has taken a valence-based approach to examine the carryover effects of incidental emotions on intertemporal choices. Some studies found that people in a negative emotional state made more immediate choices, while people in a positive emotional state made more far-sighted ones. For example, Wang and Liu (2009) found that participants in a negative emotional state would be willing to accept the smaller and immediate rewards, whereas those in a positive emotional state would be willing to wait and accept the larger and delayed rewards. This was consistent with the findings of Guan et al. (2015). Their results showed that, compared with neutral and positive emotions, negative emotion induced individuals to choose the smaller and immediate rewards. Other studies suggested that there were opposite effects of negative and positive emotions on intertemporal choices. That is, the negative state encouraged people to combat impatience, whereas the positive state made them more present biased. For example, Li and Xie (2012) found that when the decision conflict was high, participants in negative emotional states would select the larger and delayed rewards more often, relative to participants in positive and neutral emotional states. Moreover, Hirsh et al. (2010) found that extraverted individuals were more likely to prefer a smaller and immediate reward over a larger and delayed reward when first put in a positive state. In summary, these studies suggest that the effects of emotional valence on intertemporal choices are inconsistent, and specific emotions of the same valence may have different effects on intertemporal choices.

Anger and sadness are two kinds of negative emotions that are common in life. Previous studies showed that anger and sadness were associated with different facial expressions (Ekman, 2007), central nervous system activity (Phelps et al., 2014), brain hemispheric activation (Harmon-Jones and Sigelman, 2001), autonomic responses (Levenson et al., 1990), and cognitive appraisals (Smith and Ellsworth, 1985; Lerner and Keltner, 2000). The appraisal-tendency framework suggests that incidental emotions are related to specific appraisals. These appraisals reflect the core meaning of the event that elicits each emotion and determine the influence of specific emotions on judgment and decisions (Smith and Ellsworth, 1985; Lerner and Keltner, 2001). Research showed that anger was related to high certainty and control and sadness was related to medium certainty and low control (Smith and Ellsworth, 1985). Simultaneously, certainty and control were related to the cognitive factors of intertemporal choices (e.g., the unknown risk and low control of delayed options). For example, regarding intertemporal choices, studies found that longer waiting time for rewards meant greater risk of not getting it, with delayed rewards considered risky and unsafe (Benzion et al., 1989; She et al., 2010). Studies have also shown that control played an important role in intertemporal choices; that is, compared to high control, individuals with low control were more inclined to choose immediate rewards (Berns et al., 2007; Hare et al., 2009; Figner et al., 2010; Casey et al., 2011). Therefore, anger and sadness may have differential influences on intertemporal choices.

To date, few studies have examined the effects of anger and sadness on intertemporal choices. Lerner et al. (2013) investigated the effects of sadness and disgust, induced by emotional clips on intertemporal choices. Their results showed that, relative to the neutral state participants, the sad state participants preferred smaller and immediate rewards for payment. However, the disgust state participants were not more impatient than the neutral state participants. Recently, Zhao et al. (2017) explored the effects of state and trait anger on intertemporal choices. The results showed an interactive effect between state and trait anger on choice preference. When individuals were in a temporary state of high anger, high-trait anger individuals tended to prefer small and immediate rewards, compared with low-trait anger individuals; however, in a temporary state of low anger, low-trait anger individuals tended to prefer small and immediate rewards. Furthermore, their results found that the individuals' preference for small and immediate rewards was associated with less risk taking for decisions made under uncertainty, indicating that the larger and delayed rewards in intertemporal choice were risky. The above research used different emotion-inducing materials and then separately examined the influence of specific negative emotions on intertemporal choices. This study aimed to examine the effects of anger and sadness, which were primed by emotional faces, on intertemporal choices in an experiment.

Event-related potentials (ERPs) have high temporal resolution and can provide the temporal dynamics of the neural activity of intertemporal choice in milliseconds. ERP research on intertemporal choices mainly found three components. The first component, P2, is the primary evaluation component; it reflects the advanced perceptual processing of certain attributes (Kranczioch et al., 2003; Boudreau et al., 2008). Regarding an intertemporal choice task, compared with a small delayed reward amount and a short delay time, a large delayed reward amount and a long delay time induced larger P2 (Gui et al., 2016; Wu et al., 2016). These findings indicate that individuals can process the reward amount and time attributes in the early stages of decision-making. The second component, P3, is considered a measure of motivation intensity in decision-making, reflecting the influence of decision-making information on motivation level (Nieuwenhuis et al., 2005; Wu and Zhou, 2009). ERP research on intertemporal choices found that when the immediate options were presented, high-anxiety individuals had a greater P3 than low-anxiety individuals; additionally, when delayed options were presented, low-anxiety individuals had a greater P3 (Xia et al., 2017). The third component is LPP. The amplitude of LPP reflects the level of motivational participation in stimulus processing and the amount of attentional resource allocation (Delplanque et al., 2004). Regarding the intertemporal choice task, a long delay time induced a smaller LPP than a short delay time (Gui et al., 2016). Speculating from the above content, P2 reflects the processing of the advanced attributes of decision-making options, while P3 and LPP reflect the evaluation of the degree of motivation for decision-making options. Therefore, this study examined whether there were differences in the three ERP components affecting the influence of anger and sadness on intertemporal choices.

To our knowledge, most studies investigated the impact of incidental emotion on intertemporal choice by adopting a between-subjects design, in which participants were induced to a specific enduring mood state by reading autobiographical stories, watching film clips, or conducting different cognitive tasks (Wang and Liu, 2009; Hirsh et al., 2010; Raeva et al., 2010; Li and Xie, 2012; Lerner et al., 2013). However, a few studies adapted a within-subjects design to study the impact effect, in which participants were induced to a transient emotional state by emotional cues (i.e., emotional pictures or faces), during the completion of the intertemporal choice task (Luo et al., 2012; Guan et al., 2015). This study investigated the effects of anger and sadness on intertemporal choice by using ERPs. Based on the appraisal-tendency framework, anger and sadness may have different effects on intertemporal choices based on their sense of certainty and control. This study assumes that, compared with neutral and sad emotions, the high certainty and control of anger makes individuals choose large delayed rewards. This study recorded and then analyzed the ERP components in the evaluation stage, during the intertemporal choice task, thereby examining the process mechanisms of anger and sadness that influence intertemporal choices.

## MATERIALS AND METHODS

### Participants

Twenty healthy volunteers participated in the study (mean age = 19.30 ± 1.17 years, 12 females). All participants were right-handed and had normal or corrected-to-normal vision. Participants provided written informed consent and were paid for participation. This study was approved by the local ethics committee at the Department of Psychology, Ningbo University.

### Stimuli Selection

Facial images were selected from the Taiwanese Facial Expression Image Database (TFEID; Chen and Yen, 2007). The TFEID consisted of posed facial expressions (neutral, anger, contempt, disgust, fear, happiness, sadness, and surprise) by actors in training; the actors received written instructions of each emotional expression according to Ekman's intervention. Angry, sad, and neutral facial images were selected with direct gaze, front view, and high intensity. There were 30 pictures each of angry, sad, and neutral facial images; the ratio of male to female in each type of facial image was 12:18.

### Intertemporal Choice Task

We administered a modified version of the intertemporal choice task (McClure et al., 2004; Kable and Glimcher, 2007), in which participants made a series of hypothetical choices between small and immediate rewards and larger and delayed rewards. The small immediate amount was one of the three reward amounts (¥18, ¥19, and ¥20). The larger delayed option was constructed using one of the three delays (7, 15, and 30 days) and 1 of the 10 add-percentages of the immediate reward (7 days: 10, 15, 20, 30, 50, 70, 90, 120, 150, and 180%; 15 days: 15, 20, 30, 50, 70, 90, 120, 150, 180, and 215%; 30 days: 20, 30, 50, 70, 90, 120, 150, 180, 215, and 250%). The immediate reward amounts and time delay of the delayed rewards were of orthogonal design.

In each trial, a white fixation was shown for 500 ms, signaling the start of the trial. After 200–300 ms of random blank, facial images were presented for 2,000 ms. Then, the immediate and delayed offers were shown for 2,000 ms, followed by 600–800 ms of random blank space. During the choice stage, the red color of the central cue instructed subjects to make a choice within 4,000 ms. The locations of the immediate and delayed options were randomly assigned (left or right) on each trial and were counterbalanced across trials. Participants were instructed to press the "F" key to denote a left-side choice or the "J" key to denote a right-side choice (see **Figure 1**).

### EEG Recording and Analysis

Electroencephalograms (EEGs; NeuroScan Inc.) were recorded from 64 electrodes, which were mounted on an elastic cap. The horizontal electrooculogram (HEOG) and vertical electrooculogram (VEOG) were recorded as well. The left mastoid was the online reference electrode. All electrode impedances were maintained below 5 kΩ. All signals were sampled at 500 Hz and band-pass filtered within a 0.05–100 Hz frequency range. During off-line analyses, all EEG signals were re-referenced to the mean of the left and right mastoids. The EEG data were low-pass filtered below 30 Hz (24 dB/oct). Ocular artifacts were removed from the data using a regression procedure (Semlitsch et al., 1986). Trials containing EEG sweeps with amplitudes exceeding ± 70 mV were excluded.

For the evaluation stage ERPs, the EEG was averaged by channel and time window, from 200 ms before to 1,000 ms after the evaluation options presentation. According to grand-mean ERP waveforms and relevant literature (Li et al., 2012; Gui et al., 2016; Wu et al., 2016; Xia et al., 2017), we measured the peak amplitude of P1 (70–120 ms) and the mean amplitudes of P2 (200–250 ms), P3 (320–400 ms), and LPP (550–900 ms) components over the fronto-central (Fz, FCz, and Cz) and parietal areas (Pz and CPz).

### Statistics

First, based on the study of McClure et al. (2004), this study distinguished the choices into easy-to-select choices and difficult-to-select choices. The easy-to-select choices included 7 days (10–20%, 150–180%), 15 days (15–30, 180–215%), and 30 days (20–50%, 215–250%). The difficult-to-select choices included 7 days (30–120%), 15 days (50–150%), and 30 days (70–180%). The behavioral measures (the rate of immediate choices and response time) were analyzed using a two-way ANOVA, with emotion type (anger vs. sad vs. neutral) and task difficulty (easy vs. difficult) as the within-subject factors.

For the ERP components time-locked to the evaluation stage, a two-way ANOVA was used, with emotion type (anger vs. sad vs. neutral) and task difficulty (easy vs. difficult) as the within-subject factors. A Greenhouse–Geisser correction was applied to all ANOVAs when necessary. The significance levels were set at $p < 0.05$, and the marginal significance levels were set at $0.05 \leq p < 0.1$.

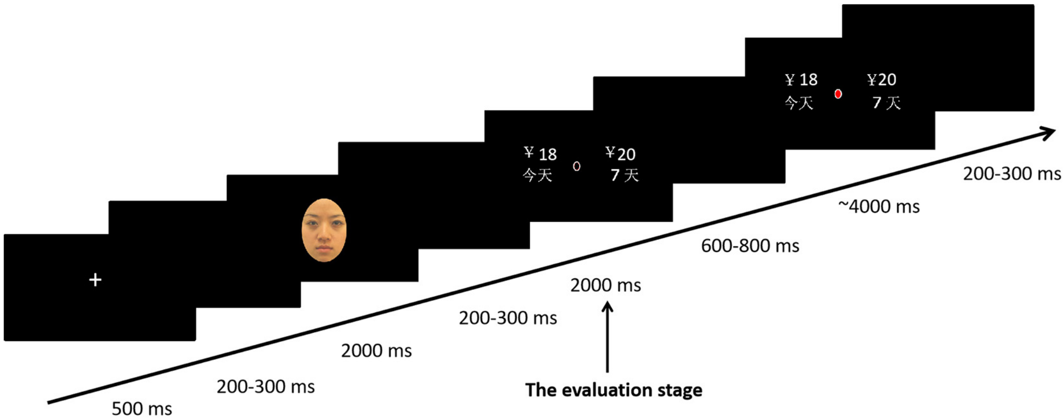


**FIGURE 1 |** Sequence of events in a single trial of the modified intertemporal choice task.

# RESULTS

In this section, we reported the behavioral and ERP results of the valuation stage. Two subjects were excluded due to severe artifacts in the EEG data, resulting in 18 participants being included for the ERP analysis. For the sake of brevity, the statistic effects that were not significant were omitted.

## Behavioral Results

**Figure 2** shows the means and SEs of the rate of immediate choices and the response time in anger, sad, and neutral prime conditions for easy-to-select and difficult-to-select choices.

For the rate of immediate choices, the main effect of emotion type was significant, $F(2, 38) = 3.42$, $p = 0.048$, $\eta^2 = 0.153$. The *post hoc* test showed that the anger prime yielded a lower rate of immediate options than neutral ($p = 0.023$) and sad primes ($p = 0.071$), with no significant difference between sad and neutral primes ($p = 0.880$). The main effect of task difficulty was significant, $F(1, 19) = 9.90$, $p = 0.005$, $\eta^2 = 0.343$, suggesting that participants making difficult-to-select choices had a higher rate of delayed options than those making easy-to-select choices (also see **Figure 2A**).

For response time, the main effect of task difficulty was significant, $F(1, 19) = 8.64$, $p = 0.008$, $\eta^2 = 0.313$, suggesting that it was significantly longer in the difficult-to-select choices than in the easy-to-select choices. The interactive effect of emotion type and task difficulty was significant, $F(2, 38) = 4.51$, $p = 0.020$, $\eta^2 = 0.192$. For the difficult-to-select choices, the anger prime yielded a significantly shorter response time than the sad prime, whereas there were no significant differences between neutral and anger primes and between neutral and sad primes ($ps > 0.100$). For the easy-to-select choices, the anger prime yielded a longer response time than the neutral prime ($p = 0.089$), and there were no significant differences between sad and anger primes and between sad and neutral primes ($ps > 0.100$). Furthermore, the response time in the difficult-to-select choices was significantly longer than that in the easy-to-select choices for sad ($p = 0.001$) and neutral primes ($p = 0.024$), whereas there was no significant difference between the easy-to-select and difficult-to-select choices for the anger prime ($p = 0.592$) (also see **Figure 2B**).

## ERPs Results

**Figure 3** shows the grand average ERPs during the evaluation stage at Fz and Pz in the anger, sad, and neutral prime conditions for the easy-to-select and difficult-to-select choices. **Figure 4** shows the topographic maps depicting voltage differences for the anger minus the neutral prime conditions, and the sad minus the neutral prime conditions in the time range of P1 (70–120 ms), P2 (200–250 ms), and P3 (320–400 ms), during the evaluation stage.

*P1(70–120 ms)*

For the fronto-central P1, the main effect of emotion type was significant, $F(2, 34) = 7.17$, $p = 0.005$, $\eta^2 = 0.297$. The *post hoc* test showed that the anger prime evoked a larger P1 than neutral ($p = 0.007$) and sad primes ($p = 0.012$), whereas there was no significant difference between sad and neutral primes ($p = 0.138$). For the parietal P1, the main effect of emotion type was marginally significant, $F(2, 34) = 3.00$, $p = 0.079$, $\eta^2 = 0.150$. The *post hoc* test showed that the anger prime evoked a larger P1 than neutral ($p = 0.036$) and sad primes ($p = 0.080$), whereas there was no significant difference between sad and neutral primes ($p = 0.331$).

*P2(200–250 ms)*

For the fronto-central P2, the main effect of emotion type was marginally significant, $F(2, 34) = 3.04$, $p = 0.070$, $\eta^2 = 0.152$. The *post hoc* test showed that the anger prime evoked a larger P2 than neutral ($p = 0.011$) and sad primes ($p = 0.086$), whereas there was no significant difference between sad and neutral primes ($p = 0.611$). For the parietal P2, there were no significant main and interactive effects of emotion type and task difficulty ($ps > 0.100$).

*P3(320–400 ms)*

For the fronto-central P3, there were no significant main and interactive effects of emotion type and task difficulty ($ps > 0.100$). For the parietal P3, the main effect of emotion type was marginally significant, $F(2, 34) = 2.77$, $p = 0.086$, $\eta^2 = 0.140$. The

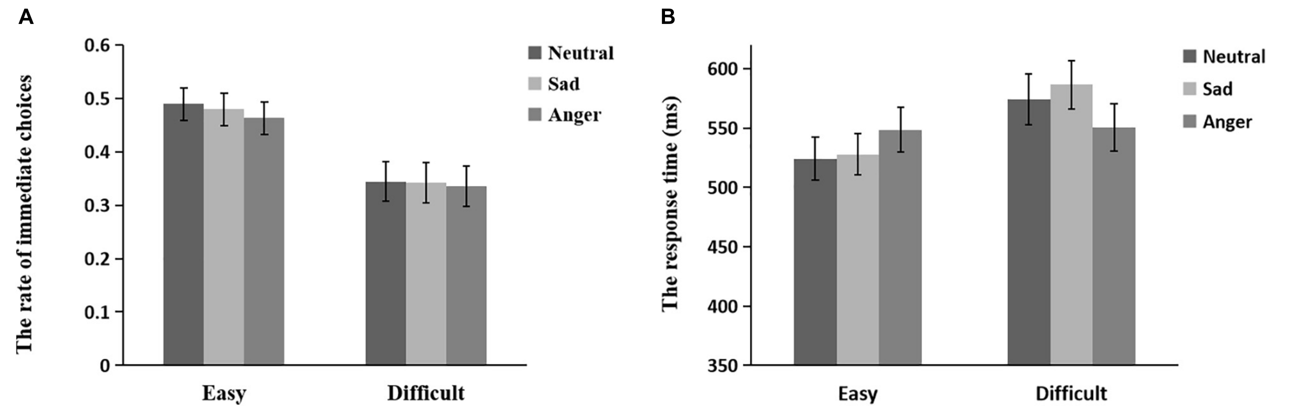


**FIGURE 2 |** The means and SEs of the rate of immediate choices **(A)** and the response time **(B)** in anger, sad, and neutral prime conditions for the easy-to-select choices and the difficult-to-select choices.

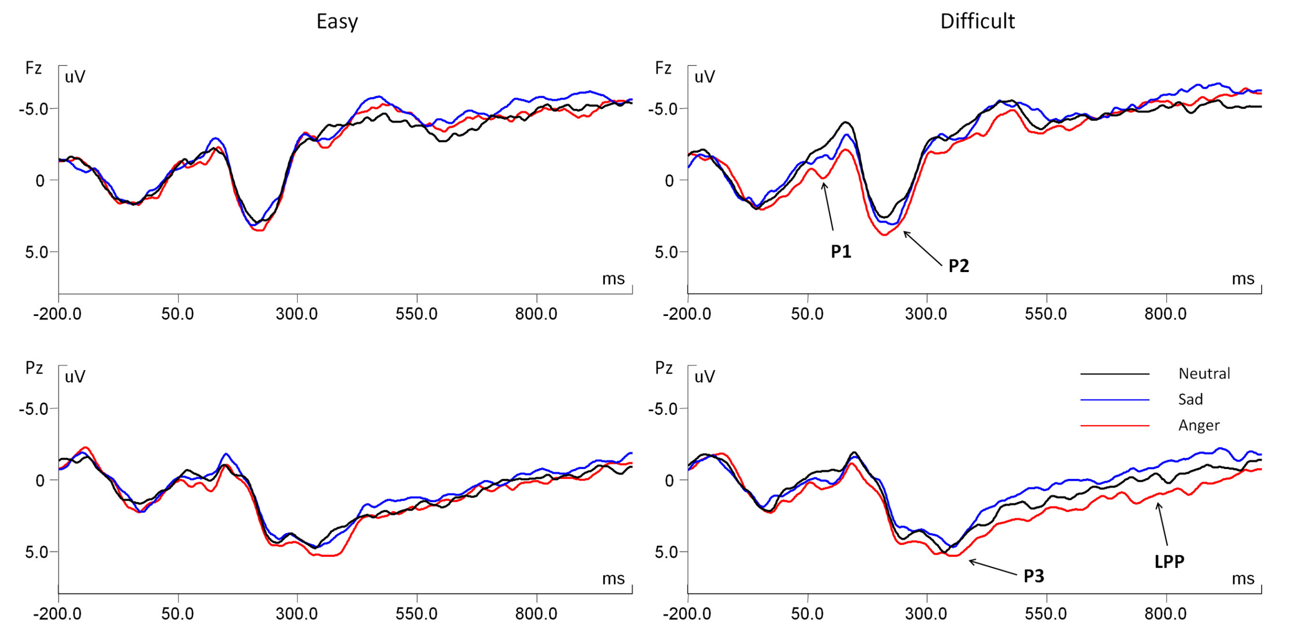


**FIGURE 3 |** Grand average ERPs during the evaluation stage at Fz and Pz in the anger, sad, and neutral prime conditions for the easy-to-select choices and the difficult-to-select choices.

*post hoc* test showed that the anger prime evoked a larger P3 than neutral ($p$ = 0.019) and sad primes ($p$ = 0.067), whereas there was no significant difference between sad and neutral primes ($p$ = 0.841).

*LPP(550–900 ms)*

For the fronto-central and parietal LPP, there were no significant main and interactive effects of emotion type and task difficulty (*ps* > 0.100).

## DISCUSSION

By combining different emotional (anger, sadness, and neutral) primes with the intertemporal choice task, this study found that anger and sad primes were differentiated in both their effects on intertemporal choice and the temporal dynamics of neural activity during intertemporal decision-making. Behavioral results showed that the anger prime (relative to neutral prime) was associated with more preference for delayed rewards. Specifically, the anger prime yielded a shorter response time than the sad prime for the difficult-to-select choices. ERP results found that the anger prime (relative to neutral and sad primes) elicited larger P1 in the fronto-central and parietal areas, P2 in the fronto-central area, and P3 in the parietal area during the evaluation stage.

This study found that, compared with the neutral prime, the anger prime encouraged individuals to prefer more delayed rewards. Based on the appraisal-tendency framework, an emotion

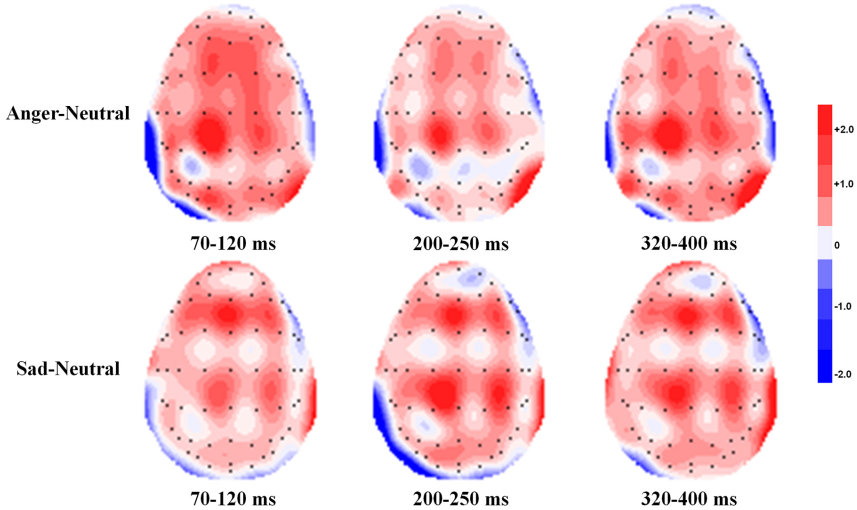


**FIGURE 4 |** Topographic maps depicting voltage differences for the anger prime condition minus the neutral prime condition and the sad prime condition minus the neutral prime condition in the time range of P1 (70–120 ms), P2 (200–250 ms), and P3 (320–400 ms) during the evaluation stage.

can have strong influences on intertemporal choices that relate to the appraisal theme of the emotion. In this study, certainty and control are central dimensions that distinguish anger from other negative emotions (Weiner et al., 1982; Averill, 1983; Smith and Ellsworth, 1985). For example, anger is related to a sense of certainty in individuals that they have enough information to feel confident in their judgment and a high coping potential that they have the capacity to deal with the situation (Smith and Ellsworth, 1985; Tiedens and Linton, 2001; Berkowitz and Harmon-Jones, 2004). Moreover, previous studies found that certainty and control were conceptually related to intertemporal choice. For example, intertemporal choices were associated with unknown risk (e.g., perceiving delayed rewards as risky and uncertain) and impulsivity (the temptation of immediate rewards) (Benzion et al., 1989; Berns et al., 2007; Hare et al., 2009; Figner et al., 2010; She et al., 2010; Casey et al., 2011). Therefore, the sense of certainty and high coping potential induced by anger can make people combat the temptation of immediate rewards, in preference for delayed rewards. Consistent with this view, this study suggested that angry individuals intended to choose larger and delayed rewards.

Generally, the response time of the intertemporal choice task can be considered as an index of the struggle between immediate and delayed options (Wu et al., 2016). This is consistent with the finding that the response time in the difficult-to-select choices was longer than that in the easy-to-select choices, indicating that there were more conflicts in the difficult-to-select choices. In this study, there was an interesting result, that for difficult-to-select choices, the anger prime yielded a shorter response time, compared with the sad prime. One possible explanation is that, compared with sadness, anger increased individuals' sense of certainty and control (Smith and Ellsworth, 1985; Tiedens and Linton, 2001), and then experiencing a sense of certainty and control motivated them to quickly make a decision from the difficult-to-select choices.

In this study, we also observed emotional prime effects on the temporal dynamics of neural activity, similar to behavioral results. First, the anger prime (relative to neutral and sad primes) elicited a larger P1 during the evaluation stage. Previous research found that P1 was sensitive to physical stimulus factors and indexed early sensory processing within the extra-striate visual cortex (Gonzalez et al., 1994; Clark and Hillyard, 1996; Luck et al., 2000). Furthermore, although P1 has been considered to be purely stimulus-driven and exogenous, there are recent findings that P1 can be influenced by high-level information, such as emotional valence, threat-related information, semantic knowledge, and reward processing (Eimer and Holmes, 2002; Smith et al., 2003; Keil et al., 2005; Rahman and Sommer, 2008; Schacht et al., 2012). For example, P1 was found to be larger for unpleasant than pleasant pictures, indicating that unpleasant pictures engaged more attentional processing than pleasant pictures (Smith et al., 2003). This study further suggested that P1 can be influenced by emotion type during the evaluation stage. That is, the anger prime makes individuals pay more automatic and fast attention to processing the intertemporal option information, compared with neutral and sad primes.

Second, the anger prime (relative to neutral and sad primes) elicited a larger P2 in the fronto-central area during the evaluation stage. Previous ERP studies on decision-making showed that the frontal P2 might reflect stimulus evaluation and quick assessment (Potts et al., 2006; Boudreau et al., 2008; Nikolaev et al., 2008; Chen et al., 2009). Specifically, ERP studies on intertemporal choice found that a larger frontal P2 was associated with a longer time delay and a larger reward amount during intertemporal decision-making, indicating the initial valuation of time and reward information (Gui et al., 2016; Wu et al., 2016). Consistent with those studies, the larger P2 in the anger prime condition might be related to the quick evaluating process involved in the information of reward amount and time delay during intertemporal decision-making.

Third, the anger prime (relative to neutral and sad primes) elicited a larger P3 in the parietal area during the evaluation stage. A previous ERP study on intertemporal choice showed that the P3 elicited by the immediate option was larger in the high trait anxiety group than in the low trait anxiety group. In addition, the P3 elicited by the delayed option was enhanced in the delayed decision condition for low trait anxiety, compared to high trait anxiety participants, indicating that the P3 is reflected to index the motivational significance of different options (Xia et al., 2017). This was consistent with the study of Li et al. (2012) that showed that an enhanced P3 has been found in individuals who show a larger delay discounting effect, indicating stronger motivations to pursue immediate over delayed rewards. In addition, the P3 was also regarded as an index to examine various advanced cognitive processes (i.e., memory encoding and updating, evaluation and stimulus categorization, and making decisions under complex social context) (Kok, 2001; Polich, 2007; Chen et al., 2009; Paynter et al., 2009; Mathes et al., 2012). In this study, our results found that the P3 amplitudes in the anger prime condition were significantly larger than in neutral and sad prime conditions, suggesting that more attentional and controlled cognitive processing resources are required in the anger prime condition and that participants had stronger motivations to select the delayed options.

This study found that, compared with neutral and sad emotions, anger, which is related to high certainty and control, made individuals choose large, delayed rewards. The study further found that anger in individuals with high certainty and control motivated them to place more attention and motivation to evaluating the choices, displaying larger P1, P2, and P3 amplitudes. If a sense of certainty and control enhances the tendency to delay gratification in intertemporal choices, positive emotions that are related to certainty and control senses should have the same effect. Future research should independently manipulate the certainty and control dimensions as well as the valence of emotions. Furthermore, it should explore whether specific emotions affect intertemporal choices through the certainty and control dimensions, while excluding their valence. In addition to using the appraisal-tendency framework to explain how specific emotions affect intertemporal choices, some researchers also used the construal level theory and the perceived-time-based model to explain this process. Specifically, the construal level theory suggested that any object or event in the environment can be characterized at different construction levels (Liberman et al., 2002): High and low construction levels. Under high-level construction, people tended to characterize long-term events, while under low-level construction, people specifically characterize recent events. The construal level theory highlights that specific emotions affect the individuals' construction level and then affect the individuals' choice preference (Wang and Liu, 2009). In addition, Zauberman et al. (2009) proposed the perceived-time-based model to explain the cognitive mechanism of intertemporal choices. They found that the discounting rate in intertemporal choices decreased as the objective delayed time increased; the reason may be that individual perception of future time is biased (Zauberman et al., 2009). The perceived-time-based model suggests that specific emotions affect the individuals' subjective perception of future time and then affect the individuals' choice preference. It remains unclear whether anger and sadness affected the individuals' construction level or subjective perception of the future time and then affected choice preference in intertemporal choices, which need further research.

This study has some limitations. First, anger and sadness were induced by emotional faces in this experiment. Although this method is one of the most common and effective methods to induce specific emotions, future research can use different emotion induction methods, including watching a video clip that induces anger and sadness, or experiencing an angry or sad event live, to determine the generality of the results of this study. Second, the sample size in this study may be too small; follow-up research needs to further expand the sample size. Moreover, the samples of this study are all composed of college students. In the future, a diverse sample (e.g., individuals of different ages) will be needed to evaluate the external validity of this study and further expand the conclusions of this experiment. Third, this study examined the influence of anger and sadness on intertemporal choices in the gain situation. Intertemporal choices involve two types of situations: Gains and losses. A large number of studies in the field of intertemporal choices have shown that the internal cognition and neural mechanisms of loss- and gain-based intertemporal choices are not equivalent, and the results obtained in the gain situation cannot be generalized to the loss situation (Gehring and Willoughby, 2002; Xu et al., 2009; Mitchell and Wilson, 2010). Therefore, it was necessary to study the influence of anger and sadness on intertemporal choices for both gain and loss situations. Fourth, previous studies found that different levels of emotional arousal also have different effects on intertemporal choices (Fedorikhin and Patrick, 2010; Sohn et al., 2015). For example, Sohn et al. (2015) examined the impact of high arousal of positive and negative emotions on intertemporal choice. The results showed that, compared with neutral emotional states, individuals tend to choose smaller timely rewards in high positive and negative emotional states. Future research needs to investigate the impact of interactions between specific emotions and arousal on intertemporal choices.

## CONCLUSION

In conclusion, this study found that anger and sadness had differential effects on intertemporal choices. That is, the anger prime motivated individuals to prefer delayed rewards, whereas the sad prime did not change the preference for intertemporal choice. The ERP results were different in P1, P2, and P3, during the evaluation stage. These findings suggest that, relative to neutral and sad primes, the anger prime motivates individuals to place more attention and motivation to evaluate their choices and makes them choose the delayed rewards.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by a local ethic committee at the Department of Psychology, Ningbo University. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

LL and TS designed the study and wrote the manuscript. XJ collected and analyzed the data and XS revised the manuscript. All authors approved the version to be published.

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# Age Influences Loss Aversion Through Effects on Posterior Cingulate Cortical Thickness

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Decision-making strategies shift during normal aging and can profoundly affect wellbeing. Although overweighing losses compared to gains, termed "loss aversion," plays an important role in choice selection, the age trajectory of this effect and how it may be influenced by associated changes in brain structure remain unclear. We therefore investigated the relationship between age and loss aversion, and tested for its mediation by cortical thinning in brain regions that are susceptible to age-related declines and are implicated in loss aversion — the insular, orbitofrontal, and anterior and posterior cingulate cortices. Healthy participants ($n$ = 106, 17–54 years) performed the Loss Aversion Task. A subgroup ($n$ = 78) provided structural magnetic resonance imaging scans. Loss aversion followed a curvilinear trajectory, declining in young adulthood and increasing in middle-age, and thinning of the posterior cingulate cortex mediated this trajectory. The findings suggest that beyond a threshold in middle adulthood, atrophy of the posterior cingulate cortex influences loss aversion.

**Keywords: decision-making, loss aversion, aging, cortical thickness, posterior cingulate, neuroimaging**

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## INTRODUCTION

The proportion of the global population that is 65 years or older is increasing faster than those of other age groups; it is estimated that by 2050, one in four people in North America and Europe, and one in six people worldwide, will be over 65 (United Nations, 2019). As older adults face a myriad of choices that involve uncertainty and loss across multiple domains, changes in decision-making can substantially impact their quality of life (Samanez-Larkin, 2013; MacLeod et al., 2017). Accordingly, the impact of aging on decision-making is of substantial interest (Löckenhoff, 2018; Lighthall, 2020). Findings have been mixed, showing worsening in some respects, particularly in more deliberative domains, such as applying decision rules (Brown and Ridderinkhof, 2009). Yet, older adults can show more optimal decision-making than their younger counterparts, especially for choices that rely on life experience and acquired knowledge (Li et al., 2013).

Many everyday decisions present a potential for loss, which increases in salience with age (Ebner et al., 2006; Depping and Freund, 2011; Mata and Hertwig, 2011; Löckenhoff, 2018). When making a choice that balances the chance of gain against the risk of loss, people of all ages tend to be risk averse and to accept a gamble only if the magnitude of the win vastly outweighs that of the loss. This phenomenon has been explained by loss aversion, which reflects the overweighing of losses compared to equivalent gains (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992). Despite reports of greater loss aversion in adults over compared to under 40

(Arora and Kumari, 2015; Kurnianingsih et al., 2015; O'Brien and Hess, 2020), other studies find no differences (Li et al., 2013; Rutledge et al., 2016; Pachur et al., 2017; Seaman et al., 2018). This discrepancy could be due to nonlinear effects of age on loss aversion, the exclusion of middle-aged participants in comparisons of older and younger groups (Li et al., 2013), or different methods of measuring loss aversion (Rutledge et al., 2016; Seaman et al., 2018).

Although aversions to risk and loss are presumably evolutionarily adaptive mechanisms (Robson, 1996; Chen et al., 2005; Zhang et al., 2014; Hintze et al., 2015), extreme sensitivity to potential loss can impair decision-making during laboratory tasks (Benjamin and Robbins, 2007; Cassotti et al., 2014) and real-world choices (Mishina et al., 2010; Herweg and Mierendorff, 2013; Schleich et al., 2019), and by people with psychiatric pathologies, such as affective disorders (Stamatis et al., 2020; Xu et al., 2020). Notably, a curvilinear relationship exists between age and both real-world financial choices (Agarwal et al., 2009) and laboratory risky decision-making (Read and Read, 2004; Tymula et al., 2013; Di Rosa et al., 2017), with better performance by middle-aged adults than their younger or older counterparts.

The goal of this study was to determine whether loss aversion followed a curvilinear relationship with age, and whether such a relationship is mediated by thickness of the insula, ventromedial prefrontal/orbitofrontal cortex (OFC), and/or anterior and posterior cingulate cortices, all of which are particularly vulnerable to age-related atrophy and are implicated in loss aversion (Tom et al., 2007; Canessa et al., 2013; Markett et al., 2016). Because risky decision-making (Tymula et al., 2013; Di Rosa et al., 2017) and associated cognitive functions (Verhaeghen and Salthouse, 1997; Brockmole and Logie, 2013; Hartshorne and Germine, 2015) follow curvilinear trajectories with age, we hypothesized that age and loss aversion would be related by a quadratic function, and that cortical thickness would influence this relationship. Considering reports that the cortical regions selected for study exhibit linear age-related thinning (Tamnes et al., 2009; Lemaitre et al., 2012; Storsve et al., 2014), we hypothesized that cortical thickness would influence loss aversion after a threshold of atrophy had been reached. Loss aversion was measured using the Loss Aversion Task, and structural MRI was performed on participants from young adulthood through middle age (17 to 54 years).

# MATERIALS AND METHODS

## Participants

Data presented here are from healthy, right-handed volunteers between the ages of 17 and 54 who participated in studies that were approved by the University of California, Los Angeles Institutional Review Board. 130 participants (40 women) completed the Loss Aversion Task and 24 were excluded during analysis of the behavioral data (see procedures for exclusion under *Loss Aversion Task* below), leaving 106 for final analysis. MRI and behavioral data from these participants, other than performance on the Loss Aversion Task, have been published in other reports (Dean et al., 2011, 2015, 2018, 2020; Ghahremani et al., 2011, 2012; Morales et al., 2012, 2015a,b; Payer et al., 2012; Zorick et al., 2012; Kohno et al., 2014; Ballard et al., 2015a,b; Jones et al., 2016; Okita et al., 2016a,b,c, 2018; Moeller et al., 2018; London et al., 2020). Recruitment utilized online and print advertisements. After initial screening, participants received detailed information about each study and gave written informed consent before screening for eligibility by physical examination, medical history, and psychiatric evaluation. Drug use history and demographic information were collected using questionnaires. Participants were excluded for medical or neurological disorders or any current Axis I psychiatric disorder except Nicotine Dependence, determined by the Structured Clinical Interview for DSM-IV (First et al., 1998). After intake, participants returned on a different day to perform the Loss Aversion Task, which was administered using identical procedures for all studies. A subset of participants ($n$ = 83) also completed structural magnetic resonance imaging (sMRI) on a different day. Data from 5 of those participants were excluded during preprocessing, leaving 78 for analysis. The average time between behavioral testing and the sMRI scan was 7 days. At intake and on each test day, participants were required to provide a urine sample that was negative for amphetamine, cocaine, methamphetamine, benzodiazepines, opioids, and cannabis. They were compensated in the form of cash, gift cards, or vouchers.

## Loss Aversion Task

The task consisted of 128 sequential monetary choices to accept or reject a mixed gamble offering a 50/50 chance of winning a certain amount of money and losing a different amount of money (e.g., gaining $30 or losing $7) (Tom et al., 2007). On each trial, an image representing a 50/50 choice was presented on the screen, and the participants indicated whether they strongly accept, weakly accept, weakly reject, or strongly reject the choice (**Figure 1A**). Four options were provided instead of two (i.e., accept or reject) to discourage reliance on rule-based choice (e.g., always accepting when the loss exceeded $5). The probability of winning or losing was kept constant at 50%, and the alternative to accepting the gamble was always to remain at the status quo (i.e., win and lose nothing). The gains ranged from $10–40 in increments of $2, and the losses ranged from $5–20 in increments of $1. Once the participant decided, the next choice was presented without showing the outcome of the previous choice; if no selection was made within 3 s, the next gamble appeared on the screen. The task was presented using MATLAB (Mathworks, Natick, MA, United States) and the Psychtoolbox[1] on an Apple PowerMac laptop computer running Mac OSX (Apple Computers, Cupertino, CA, United States), with most of the code being the same as used previously (Tom et al., 2007). Participants responded using the 1, 2, 3, and 4 keys on the keyboard.

Before testing, participants received thorough instruction on how to perform the task. Instructions were read aloud, and the participant was encouraged to ask questions while viewing training slides and performing 5–10 practice trials. To ensure that

[1] www.psychtoolbox.org

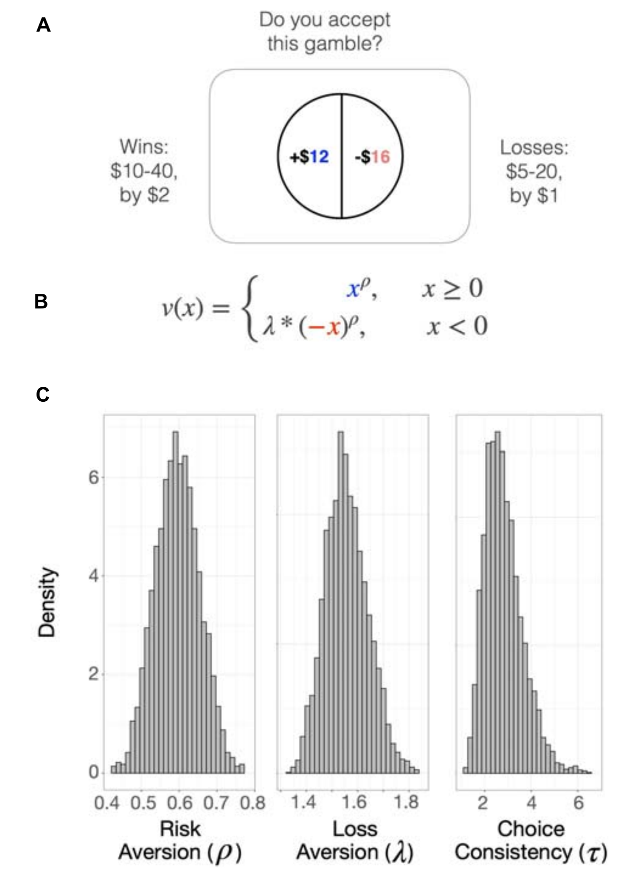


**FIGURE 1 |** The Loss Aversion Task. **(A)** The task consisted of 128 sequential monetary choices to accept or reject a mixed gamble offering a 50/50 chance of winning a certain amount of money (blue) and losing a different amount of money (red). On each trial, an image representing a 50/50 choice was presented on the screen, and the participants indicated whether they strongly accept, weakly accept, weakly reject, or strongly reject the choice. Before testing, participants received thorough instruction and practice on how to perform the task. One choice was randomly selected to be paid out at the end of the task. **(B)**. Gain ($x$) and loss ($-x$) magnitudes of each choice were inserted into the subjective value equation $v(x)$. The loss aversion parameter ($\lambda$) represents the sensitivity to potential loss relative to potential gain. Rho ($\rho$) describes the curvature of the utility function and represents attitude toward risk. **(C)** Posterior distributions of parameters estimated using hierarchical Bayesian analysis, which enables the joint estimation of individual and group parameters. The distribution densities of each parameter are plotted. Higher values of $\lambda$ indicate higher loss aversion and that the participant assigns more weight to losses than to gains of equal magnitude. When $\rho < 1$, the participant is risk-seeking for losses (more likely to take a gamble over a sure loss) and risk-averse for gains (more likely to choose a sure gain over a riskier prospect). The opposite is true when $\rho > 1$. Tau ($\tau$) is the logit sensitivity and represents choice consistency, or the sensitivity of the participant to the difference between the certain amount and the gamble.

participants were motivated on the task, they were told that one of their choices would be randomly selected to be paid out at the end of testing. They also were told that losses would be deducted from their earnings from participation in the study, but losses were not actually deducted.

The data were assessed for quality and cleaned in two ways: (1) trials with implausible reaction times (i.e., <200 ms) were excluded (0.0048% of trials); (2) data were excluded for any participant whose preferences were random, erratic, or inconsistent with trends predicted by our structural model (i.e., they were not more likely to accept the gamble for increasing magnitude of gain, decreasing magnitude of loss, or increasing expected value). Data from 24 participants were excluded.

## Behavioral Choice Modeling

Choice parameters were estimated using a multi-parameter utility function (Sokol-Hessner et al., 2009) that represents subjective value (SV) (Eq. 1) based on original prospect theory (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992):

$$\mathrm{SV}(x) = \begin{cases} x^{\rho}, x \geq 0 \\ \lambda * (-x)^{\rho}, x < 0 \end{cases} \quad (1)$$

The SV of the gamble is estimated using the objective magnitudes of gain ($x$) and loss ($-x$)given in each choice and the parameters of loss aversion (lambda; $\lambda$) and risk attitude (rho; $\rho$) (**Figure 1B**). The sensitivity to potential loss relative to potential gain is represented by $\lambda$. If $\lambda = 1$, the participant values gains and losses equally. When $\lambda > 1$, the participant is considered loss averse and assigns more weight to losses than to gains of equal magnitude. When $\lambda < 1$, the participant is considered gain-seeking, and overvalues gains compared to losses. Rho ($\rho$) describes the curvature of the utility function and represents attitude toward risk. If $\rho = 1$, the participant's preferences can be modeled by a linear utility function, which signifies that each incremental increase in reward has equal utility. Values for $\rho$ other than one indicate that the preferences of the participant can be described by a utility function that shows diminishing marginal utility. When $\rho < 1$, the participant is risk-seeking for losses (more likely to take a gamble over a sure loss) and risk-averse for gains (more likely to choose a sure gain over a riskier prospect). The opposite is true when $\rho > 1$. We did not explicitly measure risk attitudes in either the loss or gain domains.

The subjective values were then inserted into a logit (softmax) function (Eq. 2) that estimates the probability of accepting the gamble based on the difference in SVs between the lottery (50/50 choice or $\mathrm{SV}_{\mathrm{gamble}}$) and the fixed amount ($0 or $\mathrm{SV}_{\mathrm{certain}}$). The responses "strongly accept" and "weakly accept" were both treated as accepting the gamble, and both "strongly reject" and "weakly reject" were treated as rejecting the gamble. Tau ($\tau$) is the logit sensitivity and represents choice consistency, or the sensitivity of the participant to the difference between the certain amount and the gamble.

$$p\left(\text{Accept Gamble}\right) = [1 + \exp(-\tau * SV_{\mathrm{gamble}} - SV_{\mathrm{certain}})]^{-1} \quad (2)$$

Parameter values were estimated using hierarchical Bayesian analysis with the "hBayesDM" package in R (Ahn et al., 2017), which enables the joint estimation of individual and group parameters and robustly identifies individual differences in decision-making (Ahn et al., 2011). Posterior inference was performed with Markov Chain Monte Carlo (MCMC) sampling using Stan (Carpenter et al., 2017) and RStan[2]. Models were

[2] http://mc-stan.org/interfaces/rstan

validated by using the posterior distribution to generate data and visually inspecting whether the generated data corresponded to the underlying distribution.

## Structural MRI

Structural T1-weighted magnetic resonance images of the brain were acquired from 83 participants using a Magnetization Prepared Rapid Gradient Echo (MPRAGE) sequence (see **Table 1**). Images were collected from 31 participants on Scanner 1: a 1.5-Tesla Siemens Sonata MRI scanner (Erlangen, Germany) with a standard quadrature head coil (TR = 1900 ms, TE = 4.38 ms, flip angle = 15°, FOV = 160 mm × 256 mm × 256 mm, 176 slices, resolution: 1 mm × 1 mm × 1 mm). Images from 33 participants were collected on Scanner 2: a 3-Tesla Trio TIM Siemens MRI scanner (Erlangen, Germany) using parameters of TR = 2530 ms, TE = 3.31 ms, flip angle = 7°, FOV = 176 mm × 256 mm × 256 mm, 176 slices, resolution: 1 mm × 1 mm × 1 mm. Data from the remaining 14 participants were acquired on Scanner 3: a different 3-Tesla Trio TIM Siemens scanner using the same parameters.

## MRI Processing

Anatomical MRI images were processed using FreeSurfer 6.0.0[3], which generates a three-dimensional model of the cortical surface and provides measurements of local cortical thickness (Dale et al., 1999). Mean thickness within 72 automatically defined cortical parcels for each hemisphere were extracted from this model (Fischl et al., 2004; Desikan et al., 2006). Data quality was evaluated using the Qoala-T supervised learning quality control tool (Klapwijk et al., 2019), which identified data from 5 participants for exclusion, leaving data from the remaining 78 for the final analyses. As scans were acquired on different scanners, the ComBat procedure was used to harmonize the data and remove variability due to scanner type. ComBat has been validated on cortical thickness data and has been shown to robustly correct for scanner differences (Fortin et al., 2018). To preserve the variability due to age, we specified age as a biological variable for the ComBat model.

[3]http://surfer.nmr.mgh.harvard.edu

## Statistical Analysis

Statistical analyses were performed using RStudio version 1.1.456. Analysis of variance (ANOVA) or correlation, as appropriate, was used to determine whether λ was significantly associated with biological sex, race/ethnicity, estimated IQ [using the Wechsler Test of Adult Reading (WTAR) (Wechsler, 2001)], years of education of the participant's mother (as a proxy for socioeconomic status), or cigarette smoking status. As shown below, only race/ethnicity was associated with λ and was therefore included as a covariate in subsequent analyses.

A generalized linear model (GLM) was used to assess the effect of age on loss aversion. The parameter estimate (λ) from the behavioral choice model was used as the dependent variable in a GLM with the independent variable of age. Based on previous research demonstrating a curvilinear relationship between age and economic decision-making under risk (Tymula et al., 2013), a hierarchical regression analysis was used to test for a quadratic relationship between λ and age, with $age^2$ added as an independent variable for the second step of the model. On an exploratory basis, the same associations were tested with the risk attitude parameter, ρ .

The average of the mean cortical thickness of both hemispheres, weighted by cortical volume, was calculated to determine whether λ was related to whole-brain cortical thickness. Based on prior research indicating brain regions important for loss aversion (Tom et al., 2007; Canessa et al., 2013; Markett et al., 2016) and cortical thinning of the cortex with age (Tamnes et al., 2009; Lemaitre et al., 2012; Storsve et al., 2014), a region of interest (ROI) analysis was performed, including the insula, OFC, anterior cingulate cortex (ACC), and posterior cingulate cortex (PCC). ROIs were created by calculating a weighted average of both hemispheres for each region. A weighted average was also used to combine the rostral and caudal ACC to create one ACC ROI, and the medial and lateral OFC to create one OFC ROI.

To assess the main effect of cortical thickness on λ, a GLM was used for each region with λ as the dependent variable and the linear and quadratic components of cortical thickness (cortical thickness and the square of cortical thickness) as independent variables. Estimated intracranial volume was included as a covariate. Results were corrected for multiple comparisons using the Holm-Bonferroni method.

For brain regions showing significant relationships of structure with λ, a mediation analysis was performed to test whether cortical thickness mediated the relationship between age and λ. Age-related cortical thinning was confirmed using a GLM with cortical thickness as the dependent variable, age as

**TABLE 1** | Demographics of participants tested on different scanners.

| Variable | Scanner 1 (1.5 T; *n* = 31) | Scanner 2 (3 T; *n* = 33) | Scanner 3 (3 T; *n* = 14) | Omnibus statistics |
|---|---|---|---|---|
| Age, years[a] | 32.8 (1.14) | 19.9 (0.193) | 38.0 (2.76) | $F(2,75) = 61.1$, $p < 0.001$*** |
| Biological sex female/male (*n*) | 18/13 | 8/25 | 4/10 | $\chi^2(2) = 8.38$, $p = 0.015$* |
| IQ estimate standard score[a] | 105.5 (2.153) | 110.9 (1.843) | 108.4 (2.408) | $F(2,62) = 1.635$, $p = 0.203$ |
| Mother's education, years[a] | 12.3 (0.656) | 14.8 (0.690) | 13.3 (1.06) | $F(2,72) = 3.16$, $p = 0.0482$* |
| Race/ethnicity (*n*) | | | | $\chi^2(8) = 28.8$, $p < 0.001$*** |
| White | 9 | 27 | 9 | |
| African American | 6 | 1 | 0 | |
| Hispanic/Latinx | 13 | 2 | 3 | |
| Asian/Pacific Islander | 0 | 3 | 1 | |
| Other | 3 | 0 | 1 | |
| Cigarette smoking, n | 13 | 14 | 10 | $\chi^2(2) = 3.94$, $p = 0.139$ |

[a]*Unless otherwise indicated, values are means (SE).*
*IQ estimate = Weschler Test of Adult Reading.*
*$p < 0.05$; ***$p < 0.001$.*

the independent variable, and biological sex, race/ethnicity, and estimated intracranial volume tested as covariates. Age$^2$ was then added as an independent variable for the second step of the model to check for any nonlinear effects of age.

The mediation model tested whether cortical thickness mediated the effect of age on λ. Because of the quadratic relationship between age and λ, age$^2$ was specified as the independent variable, with age and estimated total intracranial volume as covariates. To account for any nonlinearities, the square of cortical thickness was also included as a covariate. The mediation analysis used the "mediations" specification of the "mediation" package in R, which enables nonparametric causal mediation analysis (Imai et al., 2010, 2013). Indirect effects, given by the Average Causal Mediation Effects (ACME), were computed using Monte Carlo simulations, and the 95% confidence intervals were computed by determining the effects at the 2.5 and 97.5th percentiles.

## Data Availability

All loss aversion task and cortical thickness data discussed in this manuscript, as well as the code used for statistical analyses, are publicly available at Open Science Framework under project title "Age Influences Loss Aversion Through Effects on Posterior Cingulate Cortical Thickness"[4].

# RESULTS

## Relationship Between Loss Aversion and Demographic Variables

Biological sex, estimated IQ, cigarette smoking status, and years of mother's education had no significant effects on λ ($p$s > 0.05), and, therefore, were not included in subsequent analyses (results were consistent when measures of socioeconomic status, such as father's education, were used instead of mother's education). An ANOVA revealed differences in λ based on race/ethnicity [$F(4,101) = 5.78$, $p < 0.01$], with post-hoc t-tests illustrating that Caucasians had higher λ than all other groups ($p$s < 0.05), and Hispanic/Latinx had higher λ than African Americans ($p < 0.05$); all other pairwise comparisons were nonsignificant ($ps$ > 0.05). Based on these findings, subsequent analyses used race/ethnicity as a covariate which was coded as 1 = Caucasian, 2 = Hispanic/Latinx, 3 = African American, and 4 = Other.

## Quadratic Relationship Between Loss Aversion and Age

In data from the full sample, parameter estimates of the behavioral choice model, estimated using hierarchical Bayesian analysis, were consistent with published values (Tom et al., 2007; Sokol-Hessner et al., 2009, 2012). Posterior distributions of the parameters are shown in **Figure 1C**. Means with standard errors and ranges were: λ = 1.58 (0.04; 0.76 – 2.61; loss aversion), ρ = 0.60 (0.0036; 0.44 – 0.70; risk attitudes), τ = 3.07 (0.09; 0.96 – 6.74; choice consistency) and reaction time = 1.45 (0.0059; 0.206 – 4.49). When the quadratic variable of age was added to the model, both age [β = −0.067, $t(97) = -2.24$, $p = 0.028$] and age$^2$ [β = 0.0010, $t(97) = 2.309$, $p = 0.023$] had significant effects, and the model fit the data better than the linear model [ANOVA; $F(97,98) = 5.33$, $p = 0.02$, change in $R^2 = 0.0433$; **Figure 2A**].

The curvilinear association between λ and age persisted in the subsample from which sMRI data were acquired ($n = 78$); when the quadratic variable of age was added to the model, both age [β = −0.0722, $t(75) = -2.36$, $p = 0.021$] and age$^2$ [β = 0.0011, $t(75) = 2.46$, $p = 0.016$] were significantly related to λ. The quadratic model provided a significantly better fit for the data than the linear model [ANOVA; $F(75,76) = 6.074$, $p = 0.016$; change in $R^2 = 0.070$].

## Mediation by Posterior Cingulate Cortical Thickness of the Age Effect on Loss Aversion

### Main Effects

Mean overall cortical thickness was not significantly related to loss aversion (β = 0.072, $t(77) = 0.152$, $p = 0.88$) and was therefore excluded from subsequent analyses. There were neither linear nor quadratic main effects of cortical thickness on λ in the insula [linear: β = −2.529, $t(73) = -0.248$, $p = 0.805$; quadratic: β = −0.467, $t(73) = -0.278$, $p = 0.782$], OFC [linear: β = 6.77, $t(73) = 0.498$, $p = 0.620$; quadratic: β = −1.32, $t(73) = -0.515$, $p = 0.608$], or ACC [linear: β = −1.209, $t(73) = -1.071$, $p = 0.288$; quadratic: β = 2.097, $t(73) = 1.030$, $p = 0.306$]. Although there were effects of both the linear and quadratic components of PCC thickness on λ [linear: β = −1.672, $t(73) = -2.148$, $p = 0.035$; quadratic: β = 3.30, $t(73) = 2.13$, $p = 0.037$], neither survived Holm-Bonferroni correction for multiple comparisons.

### Mediation Analysis

Age-related cortical thinning of the PCC followed a linear course [β = −0.00728, $t(73) = -5.19$, $p = 0.00000182$; **Figure 2B**], with a small quadratic component [β = −0.000243, $t(72) = 1.712$, $p = 0.091$]. PCC thickness significantly mediated the age-loss aversion relationship, as quantified by the ACME ($p = 0.028$; **Figure 2C**). Since linear age-related change in the PCC was confirmed, but age and λ were quadratically related, we examined which component of the λ-age relationship was mediated by PCC thickness. To visualize the relationship between λ and PCC cortical thickness for different ages, we plotted the relationship between PCC thickness and λ by age for younger (<35) and older (>35) participants (**Figure 2D**). We split the data at the age of 35 as this was the inflection point of the age-loss aversion quadratic. The plot suggests that the mediation analysis captures an effect of PCC thickness on loss aversion that shifts throughout the lifespan, potentially mediating the increase in loss aversion in later life as opposed to the decrease in young adulthood.

## Exploratory Analyses: Risk Attitudes (ρ) and Brain Structure

The risk attitude parameter (ρ) was not significantly correlated with age [β = −0.000520, $t(98) = 0.83$, $p = 0.408$] or the quadratic variable of age [β = 0.0000266, $t(97) = 0.494$, $p = 0.622$].

[4]https://osf.io/ejr56/

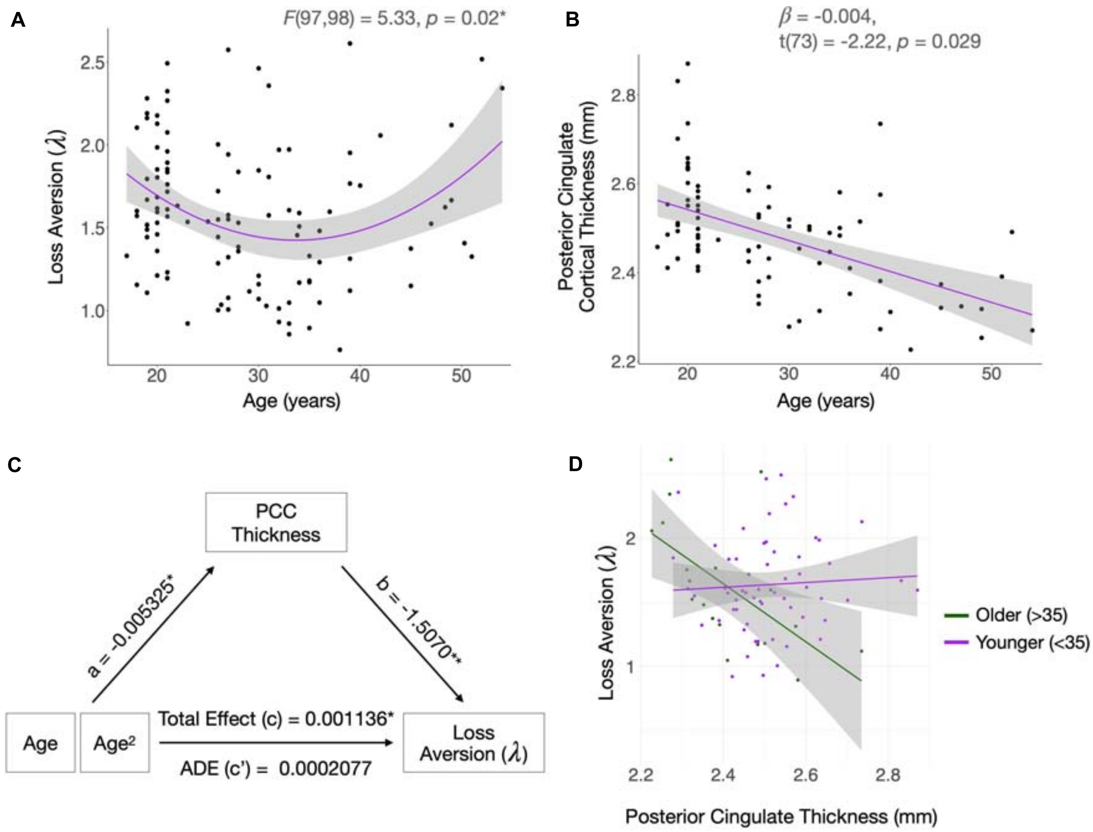


**FIGURE 2 |** Relationships between age, loss aversion, and cortical thickness. **(A,B)** Loss aversion (λ) follows a quadratic trajectory with age, whereas cortical thickness of the posterior cingulate cortex (PCC) declines linearly with time. Shading indicates standard error confidence intervals. **(C)** Cortical thickness of the PCC mediates age-related changes in λ. The effect of age on PCC thickness is given by "a." The effect of PCC thickness on λ is given by "b." The Average Direct Effect (ADE; "c") is the effect of age on λ when controlling for the mediator of PCC thickness. To calculate the Total Effect (c) of age on λ, without accounting for the mediator, both age and age$^2$ were included in the model and the regression coefficient for age$^2$ was taken as the strength of the effect. The causal mediation analysis was performed using nonparametric bootstrap confidence intervals and Monte Carlo simulations. The model included age, age$^2$, race/ethnicity, scanner, and estimated intracranial volume, as well as PCC thickness as the mediator. Age$^2$ was specified as the variable of interest. The measure of significance was given by the Average Causal Mediation Effect (ACME; $p = 0.018$*). Asterisks denote statistically significant results. *$p < 0.05$, **$p < 0.01$. **(D)** A negative relationship between PCC thickness and λ exists in older participants, but no relationship is present in participants under 35 years. The age of 35 was used to split the data into younger and older groups as it approximates the inflection point of the age-λ quadratic.

There were no main effects for cortical thickness or the cortical thickness$^2$ on risk attitudes in any of the four ROIs: insula [linear: $\beta = 0.499$, $t(73) = 0.489$, $p = 0.626$; quadratic: $\beta = -0.0764$, $t(73) = -0.454$, $p = 0.651$]; OFC [linear: $\beta = -0.083$, $t(73) = -0.061$, $p = 0.951$; quadratic: $\beta = 0.0151$, $t(73) = 0.058$, $p = 0.954$]; ACC [linear: $\beta = -0.724$, $t(73) = -0.633$, $p = 0.529$; quadratic: $\beta = 0.130$, $t(73) = 0.631$, $p = 0.530$]; PCC [linear: $\beta = 1.144$, $t(73) = 1.439$, $p = 0.154$; quadratic: $\beta = -0.222$, $t(73) = -1.401$, $p = 0.165$].

# DISCUSSION

With the global population of those 65 years and older growing faster than all other age groups (United Nations, 2019), an understanding of the trajectory of decision-making over the lifespan may help people make better choices as they age (Agarwal et al., 2009; MacLeod et al., 2017). Providing unique insight into the relationship between aging and decision-making, this study found an association between age and loss aversion that followed a quadratic function, declining across young adulthood and reaching a minimum around age 35 before increasing in middle-age. We also showed that PCC thickness mediates the relationship between age and loss aversion, suggesting that cortical thinning of the PCC is likely one of several factors that contribute to changes in decision-making throughout the lifespan. Because we also confirmed that PCC thickness declines linearly with age (Tamnes et al., 2009; Lemaitre et al., 2012; Storsve et al., 2014), PCC thinning may emerge as an important factor in loss aversion when a certain threshold of atrophy begins in middle age.

A nonlinear relationship between age and loss aversion could unify seemingly conflicting results in the literature. Previous studies may have captured components of the quadratic relationship: participants aged 25–40 were less loss averse than those aged 41–55 (Arora and Kumari, 2015), and participants

∼18–28 were less loss averse than those aged ∼60–86 years (Kurnianingsih et al., 2015; O'Brien and Hess, 2020). Others may have missed differences due to the nonlinearities observed here (Li et al., 2013; Pachur et al., 2017). Our findings conflict with certain studies that did not find a quadratic relationship between age and loss aversion (Gächter et al., 2010; Rutledge et al., 2016; Seaman et al., 2018), which may be accounted for by the use of different tasks and methods to measure loss aversion (Gächter et al., 2010; Rutledge et al., 2016; Seaman et al., 2018). Nevertheless, the loss aversion and risk preference parameters were very similar to those recently reported in a study that fit a prospect theory utility function to choice data from 146 participants (Ackert et al., 2020).

The quadratic relationship between loss aversion and age mirrors the developmental trajectory of the cortex, during which the neurobiological mechanisms of cortical thinning differ in development and aging (Vidal-Pineiro et al., 2020). Cortical maturation includes thinning in sensory and eventually fronto-cortical areas, and may extend beyond the mid-twenties (Tamnes et al., 2009), whereas cortical thinning approaching middle-age could be considered the onset of senescence (Salat et al., 2004). Thus, PCC thickness may be unrelated to loss aversion during cortical maturation, but may arise as a contributing factor once cortical thinning is underway.

With normal aging, functional changes include the reduction of the integration of coordinated activity between brain regions and increases in the localization of function within regions (Bishop et al., 2010). Such reorganization can contribute to shifts in the mechanisms underlying decision-making, perhaps increasing reliance on certain regions and not others. The PCC has been linked to the representation of subjective value during probabilistic choice tasks (Kable and Glimcher, 2007; Levy et al., 2010), reward signaling (McCoy et al., 2003), attentional focus (Leech and Sharp, 2013), and the dynamic adaptation of behavior (Pearson et al., 2011). Beyond a threshold of cortical thinning of the PCC, such functions may be impeded, rendering the most adaptive strategy that which is the least cognitively demanding (Mata et al., 2007). Such adaptations could manifest in the use of an automatic or default heuristic, such as loss aversion, as shown by older adults using less cognitively taxing strategies in paradigms that involve risk (Weller et al., 2011). The plasticity of the brain coupled with an adaptive response to shifting cognitive resources (Gutchess, 2014) may result in older adults opting for choices that are "good enough" instead of searching to maximize outcomes [i.e., using "satisficing" instead of maximizing strategies (Kurnianingsih et al., 2015)]. During probabilistic choices involving loss, older adults are more likely to use such strategies when making decisions related to finances (Chen and Sun, 2003) and health (Besedeš et al., 2012). Satisficing strategies are related selectively to loss aversion and not to risk preferences; those who have greater loss aversion tend to stop searching for an optimal solution sooner (Schunk and Winter, 2009).

Notably, the Loss Aversion Task does not measure adaptive decision-making, and a loss-aversion strategy is not necessarily disadvantageous. Older individuals do not indiscriminately make worse decisions (Wood et al., 2005; Li et al., 2013, 2015; Bruine de Bruin et al., 2014), and heightened loss aversion may reflect naturally occurring shifts in values and motivations (Depping and Freund, 2011; Hess, 2014). Changes in cognitive faculties with age are not linear across time nor uniform across domains; the age-related decline of certain cognitive faculties, such as processing speed, episodic memory, and executive functions (Baltes and Lindenberger, 1997; Salthouse, 2019), may lead older adults to revert to a previously learned response, such as loss aversion, that requires less cognitive effort. Meanwhile, prioritizing the use of abilities that remain intact or even improve with age, such as those that depend on experience, emotional intelligence, and crystallized intelligence, may improve efficiency (Peters et al., 2007; Hess, 2014; Hartshorne and Germine, 2015; Zaval et al., 2015). Similarly, while young adults can take more risk than older adults, risk-seeking as measured in the laboratory is separable from loss aversion (Köbberling and Wakker, 2005). Thus, it is possible for a participant to display a certain level of loss aversion in the face of uncertain gambles but still be risk-seeking when presented different options.

The PCC also is implicated in emotional processing, as it is activated by emotional words (Maddock et al., 2003) and attending to emotional states (Terasawa et al., 2013). Emotional processing is necessary for adaptive decision-making (Loewenstein, 1996; Mellers et al., 1999; Phelps, 2009), and loss aversion is linked to the ability to regulate (Sokol-Hessner et al., 2009, 2012), and process (Bibby and Ferguson, 2011) emotions. Such faculties peak around age 45–60 (Hartshorne and Germine, 2015), and emotional content is particularly salient for older adults (Carstensen and Turk-Charles, 1994; Fung and Carstensen, 2003). Since reliance on emotional information can compensate for age-related declines in cognitively challenging situations (Hanoch et al., 2007; Peters et al., 2007), increases in loss aversion with age may reflect greater focus on emotional or experiential dimensions of decision-making. Related to emotional processing is interoception, which is also associated with the PCC (Kleckner et al., 2017; Stern et al., 2017) and tied to loss aversion (Sokol-Hessner et al., 2015). Thus, age-related cortical thinning in the PCC may hinder the ability to efficiently integrate affective responses into complex choices, especially those that include loss.

The present moment also gains salience with age, and prioritizing immediate or emotional wellbeing may intensify as time horizons constrict (Carstensen, 2006; Löckenhoff, 2011). Converging evidence, including self-reported goal orientations and performance on a probabilistic gambling task (Ebner et al., 2006; Depping and Freund, 2011; Mata and Hertwig, 2011), indicates a shift later in life toward avoiding losses instead of seeking gains. In fact, loss orientation in later adulthood is correlated with subjective well-being (Ebner et al., 2006). When motivations shift toward optimizing immediate, emotional wellbeing and processing power becomes limited with age, perhaps partly because cortical thinning of the PCC impedes probabilistic assessments, loss aversion may naturally emerge as a low-effort response when facing choices with uncertainty.

Higher loss aversion in younger participants and its subsequent decline across young adulthood may similarly reflect the underdevelopment of complex probabilistic decision-making (Weller et al., 2011; Beitz et al., 2014). The Loss Aversion Task requires the time-limited integration of the magnitude and probability of both reward and loss to decide whether the chance of reward is worth the risk of loss; this estimation of subjective value is critical to adaptive choice behavior. Sensitivity to the difference in expected value between options follows an inverted U-shaped function, suggesting that the ability to distinguish appropriately between reward-based options may not fully develop until the mid-20s (Weller et al., 2011).

While the age range of 17 to 54 covered in the current study does not represent the entire lifespan, prior studies point to the trajectory of the quadratic relationship observed here. Loss aversion was a main driver of behavior in children as young as 5–8 years old (Steelandt et al., 2013), and adults older than those examined here (aged 61–86) exhibited greater loss aversion than young adults (Kurnianingsih et al., 2015; O'Brien and Hess, 2020), consistent with the upward trend we observed from ages 35–54. Another limitation of this study is imbalance and relatively small samples of men and women; therefore, conclusive statements about effects of biological sex on loss aversion were not possible. That race/ethnicity was a significant factor in loss aversion also merits further investigation. The lack of an effect of age on risk-taking may reflect the type of task used, as the Loss Aversion Task is not necessarily designed to comprehensively elicit risk preferences. Finally, although there was no significant association between loss aversion and PCC thickness when correcting for multiple comparisons, lack of significance apparently reflected nonlinearities in the relationship – a negative correlation of loss aversion with PCC thickness in older participants, who had smaller PCC thickness, but not in participants whose PCC thickness crossed the inflection point on the U-shaped curve.

We conclude that cortical thickness of the PCC may supplement other cognitive and neurobiological age-related changes and arise as an important factor for loss aversion around the onset of age-related atrophy. Tracking age-related changes in the influence of decision-making biases, such as loss aversion, can inform policies that are tailored to the aging population (Samanez-Larkin, 2013). Moreover, determining the age at which changes begin can introduce opportunities for early intervention, such as services, education, or incentives that could better inform important life decisions, such as those related to health and finances (Johnson and Goldstein, 2003; Agarwal et al., 2009; MacLeod et al., 2017). Identification of brain regions that affect such choices when altered with age provides the opportunity to forecast – and perhaps forestall – future decision-making impairments. To this end, future longitudinal studies may go beyond cross-sectional investigations to use measurements from key brain regions (e.g., PCC) at mid-life to predict changes in decision making biases later in life.

## DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: Open Science Framework under project title "Age Influences Loss Aversion Through Effects on Posterior Cingulate Cortical Thickness" (https://osf.io/ejr56/).

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of California, Los Angeles Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

DG, AD, EL, and ZG contributed to conception and design of the study. ZG performed the behavioral analysis and performed the statistical analyses and wrote the first draft of the manuscript. J-BP performed the cortical thickness analysis. All authors contributed to manuscript revision, and read and approved the submitted version.

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# How Neurobiology Elucidates the Role of Emotions in Financial Decision-Making

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Over the last 15 years, a revolution has been taking place in neuroscience, whereby models and methods of economics have led to deeper insights into the neurobiological foundations of human decision-making. These have revealed a number of widespread mis-conceptions, among others, about the role of emotions. Furthermore, the findings suggest that a purely behavior-based approach to studying decisions may miss crucial features of human choice long appreciated in biology, such as Pavlovian approach. The findings could help economists formalize elusive concepts such as intuition, as I show here for financial "trading intuition."

**Keywords: emotions, financial decisions and choices, choice theory, neurobiology, neurofinance, decision neuroscience, biomarkers**

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## HIGHLIGHTS

- Neurobiology provides non-behavioral evidence for traditional theories of choice, not only rationalizing them, but also potentially enhancing their out-of-sample predictive power.
- Neurobiology clarifies the true links between economic concepts (e.g., risk aversion), psychological concepts (e.g., feelings), biological ideas (e.g., emotions, genotype) and medical phenomena (e.g., neurological and psychiatric illnesses).
- Neurobiology helps to make sense of elusive concepts such as "gut feeling" or "financial intuition."
- Emotions are already partially embedded in some of the mathematics of neoclassical choice theory because affection is an integral part of cognition: we decide not only with our brain, but also with our body.
- Neurobiology identifies, from biomarkers, aspects of choice that have been overlooked in traditional behavioral research (e.g., Pavlovian approach-avoidance reflexes).

## INTRODUCTION

Decision scientists make sense of observed behavior using "as if" models. In economics, agents choose "as if" optimizing; in psychology, a person avoids gambles "as if" losses loomed larger than gains. Here, we will argue that neurobiology allows decisions scientists to go beyond "as if" modeling. This helps explain, among others, behavioral heterogeneity (why is it that some people are more susceptible to loss/gain framing than others?), and to identify aspect of behavior that have been overlooked in a behavioralist approach (such as Pavlovian approach-avoidance behavior, which is important to understand the genetics behind risk attitudes).

Our arguments will be based on an example. Recently, a group of neuroscientists and economists published an article in *Scientific Reports* that showed how intero-ceptive ability correlated with trading success on a London trading floor (Kandasamy et al., 2016). Specifically, it showed how professional traders' ability to sense their own heartbeat was better than that of the population at large and that this intero-ceptive ability correlated positively with their profit/loss performance, and with job tenure (**Figure 1**). These findings caused the *Financial Times* to conclude, rather sensationally, that "gut feeling" will eventually allow humans to beat robots (algorithmic traders)[1].

Indeed, robots don't have hearts, so how can they ever acquire the intero-ceptive ability that traders appear to need to be successful? As we shall see, the answer to this question requires a deeper understanding of neurobiology. Is it really true that the human heart plays a role in human cognition that cannot be captured by a "rational" algorithm? Are emotions, of which heartbeat is one measure, orthogonal to rationality?

As we shall see, the heart in fact plays an integral role in rational decision-making. As do emotions in general. This is one of the main insights of recent studies of the neurobiology behind decision-making, i.e., *decision neuroscience.* The implications for economics and psychology, where emotions and reason are still widely believed to be antithetic, exceptions notwithstanding (Lerner et al., 2015), are profound.

The authors of the *Scientific Reports* study do not claim causality. As such, financial firms better not jump to the conclusion that they should hire traders on the basis of ability to sense their heartbeat.

Instead, the finding corroborated 15 years of research on the neurobiological foundations of human risk assessment and risk taking. Indeed, the finding really only makes sense if put into perspective against that research. It proved that this research can explain a strong, yet most puzzling link that exists between intero-ceptive ability and trading performance in financial markets. In fact, without the background research, one can quite reasonably question the validity of the finding, since it emerged in a sample of only 18 subjects (plus controls). The finding is only one piece in a chain of converging evidence on the role of one particular expression of emotional engagement, heartbeat, in successful financial decision-making.

To understand the link between the heart and decision-making in the context of risk and uncertainty, we first have to explore the links between the heart, the brain, and one key financial variable: volatility (or risk). What is to follow is a fascinating exploration of recent, seemingly unrelated findings, in financial decision-making and in neurobiology. Each finding is a piece in the puzzle that explains why traders who sense their heartbeat better make more money.

The goal of this article is not to provide a comprehensive review of the role of emotions in financial decision-making, and the neuroscience behind it. Instead, the article is meant to be a pedagogical tool for social scientists, and in particular finance scholars, to better comprehend, through a pointed example, how and why emotions form an integral part of reasoned decision-making. On the neuroscience side, for instance, the focus will be on a region called anterior insula, at the expense of other regions intimately connected to emotions, such as amygdala, anterior cingulate cortex, or even posterior parts of insula. The reason is simple: anterior insula has been associated with detection of heartbeat changes and conversion of those into anticipation of changes in the environment.

## FINANCIAL RISK CHANGES CORRELATE WITH ACTIVATION IN NORADRENERGIC NEURONS WHICH DRIVE HEARTBEAT CHANGES

"So what are policymakers to do? First and foremost, reduce uncertainty. Do so by removing tail risks, and the perception of tail risks." This statement, by the chief economist of the IMF[2], summarizes what is unique about uncertainty generated in financial markets, namely, tail risk. Technically, one refers to leptokurtosis: outliers are far more prevalent than under the Gaussian distribution, and because small price changes are also more frequent, the outliers are immensely salient (see **Figure 2A**). It is thought that continuous changes in volatility generates this leptokurtosis (**Figure 2B**). GARCH (Generalized Autoregressive Conditional Heteroscedasticity) is one popular way to model volatility changes, and hence, leptokurtosis (Bai et al., 2003) (see also **Box 1**). There, outliers reveal increases in volatility.

Outliers often revert, and automated high-frequency traders attempt to exploit those reversals, banking on the statistical regularity that reversals occur more frequently (Brogaard et al., 2018). That is, leptokurtosis often constitutes noise that can be taken advantage of, which is why it has been referred to as *leptokurtic noise* (D'Acremont and Bossaerts, 2016).

One can generate changes in volatility in a controlled setting, and study how the human brain reacts to it. Inserting electrodes into the brain is too invasive to be used in healthy humans and non-invasive methods like functional magnetic resonance imaging (fMRI) are too expensive and too elaborate to be used outside the lab (see **Box 2**). Fortunately, there are more easily accessible physiological measures that can serve as a proxy for the activity in particular brain regions. For instance, pupil dilation is known to reflect activation of the locus coeruleus (LC), a cluster of neurons in the brainstem, that mostly use the chemical norepinephrine (noradrenaline) to communicate with downstream neurons (see **Box 3**). The noradrenergic system is a key component of the attentional network in the brain. Noradrenaline in the brain increases arousal and alertness but also restlessness. As such maladaptive responses of this network are thought to be responsible for mental disorders such as Attention Deficit Hyperactivity Disorder (ADHD) and anxiety. Medications such as reboxetine (inhibitor) or guanfacine (agonist) regulate the noradrenergic system.

[1]"Man v machine: 'Gut feelings' key to financial trading success." *Financial Times* 19 Sep 2016.

[2]Olivier Blanchard, chief economist, IMF, *The Economist* 31 January 2009.

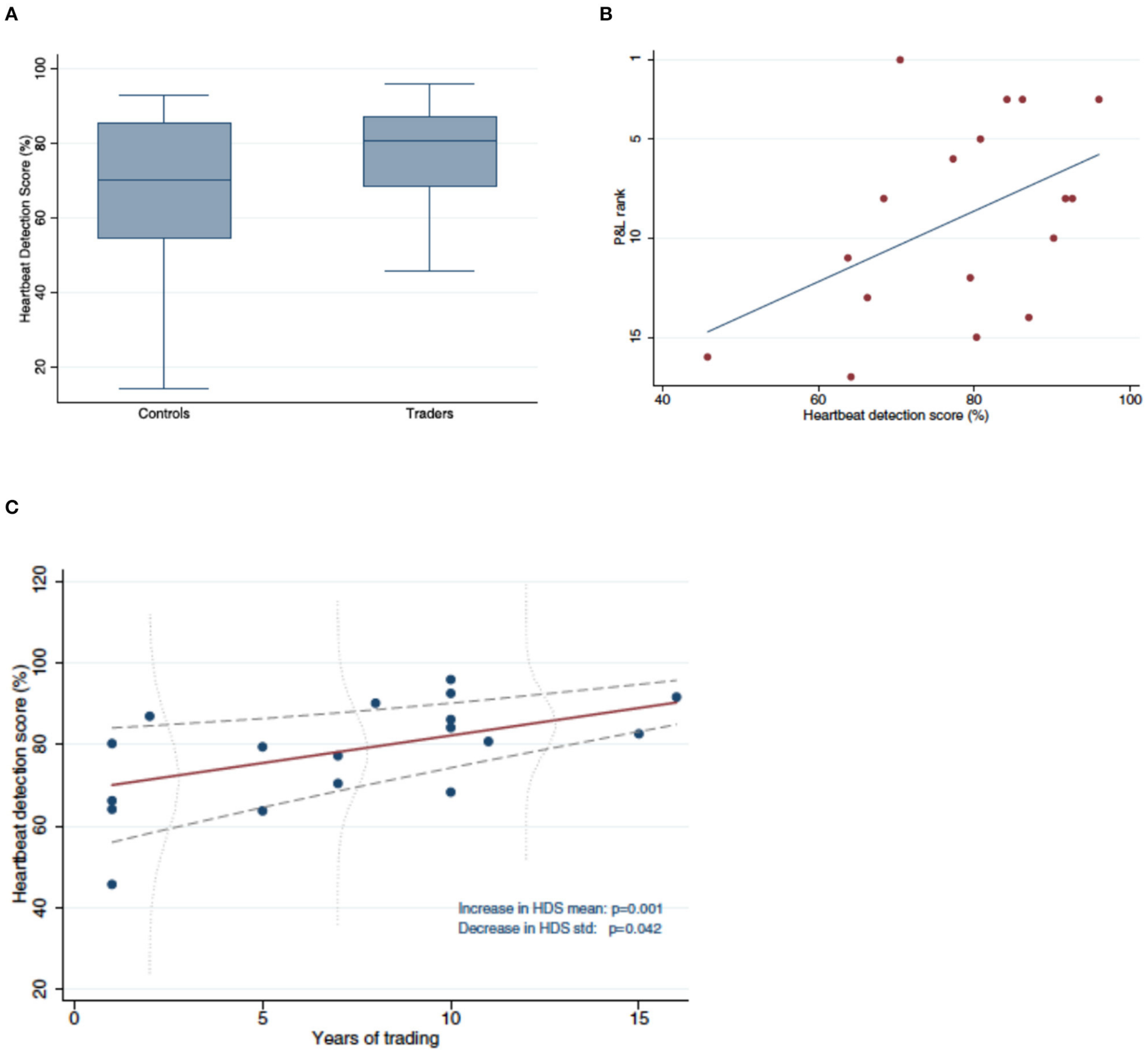


**FIGURE 1 | (A)** Traders have significantly better heartbeat detection than Controls. Shown are boxplots of heartbeat detection scores for Traders (right) ad Controls (left). **(B)** More successful Traders have better heartbeat detection. Shown is the relation between heartbeat detection score and profit/loss (PandL) rank. **(C)** Traders with longer tenure have better heartbeat detection. Shown is the relation between years in trading and heartbeat detection score. Source: Kandasamy et al. (2016).

Preuschoff and collaborators exploited this link between pupil dilation and noradrenaline to study the effect of (changes in) volatility on neural activity. They had participants play a simple card game. To suppress changes in pupil dilation due to changes in luminosity (the well-known pupillary light reflex), all stimuli were presented aurally rather than visually (Preuschoff et al., 2011). Throughout the card game, volatility (measured as standard deviation of expected payoff) changed constantly. The researchers found that pupil dilations were strongly correlated with mistakes in predicting volatility. That is, pupil dilations "measured" risk prediction errors – the driving term in the popular GARCH processes. Remember that the task was entirely auditory and these changes can therefore not be explained by changes of luminosity in the surroundings. Instead the changes in pupil dilation likely reflected changes in neural activity – most likely the activity of noradrenergic neurons in LC or its afferent (upstream) and efferent (downstream) brain circuitry.

Noradrenergic neurons have projections into many parts of the brain, such as the pre-frontal cortex and the visual cortex. In addition, some projections reach the heart without

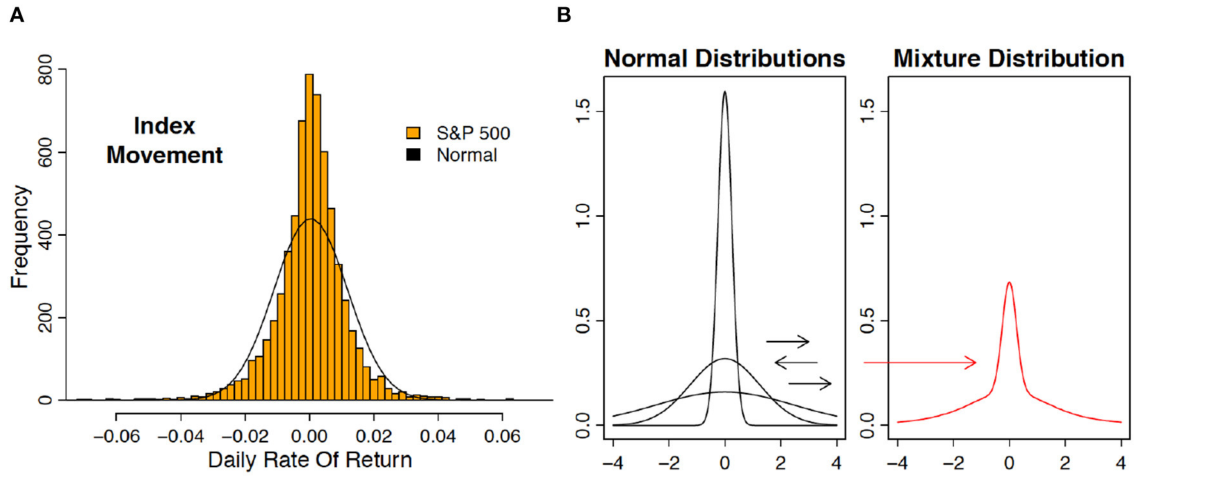


**FIGURE 2 | (A)** The distribution of daily rate of return on the SandP 500 index is leptokurtic. Shown are the histogram of daily returns (1 June 1988–28 June 2013) and a Gaussian curve fit to the same data. If the Gaussian distribution had been correct, then a daily return over 4% in absolute value is expected to occur only once every 128 years. Over the 25 years displayed here, there were 41 such outliers. **(B)** Leptokurtosis can be obtained by shifting variance. Shown are three Gaussian curves with different variances (left). Repeated drawing by first choosing a variance and then drawing from the corresponding Gaussian curve ("mixing") produces a leptokurtic distribution (right).

**BOX 1** | GARCH and neural signaling in Anterior Insula.

Neural signals in the Anterior Insula (AI; see **Box 4**) track errors in forecasting volatility. A popular way in financial econometrics to model changes in volatility is the Generalized Conditional Heteroscedasticity (GARCH) model (Bai et al., 2003). In its simplest form, this model assumes that return volatility $\sigma_t$ over time t follows a first-order autoregressive process, driven by deviations from the mean $(e_t)^2$:

$$(\sigma_{t+1})^2 = \phi(\sigma_t)^2 + \psi(e_t)^2,$$

where

$$e_t = r_t - \mu,$$

i.e., the shock $e_t$ equals the deviation of the return on an asset over a period $r_t$ from its expectation $\mu$. The changes in volatility leads to "mixing," which induces leptokurtosis in the return data. Preuschoff et al. (2008) discovered that Anterior Insula (AI) tracks risk prediction errors, defined as mistakes in volatility predictions. In the notation of the above GARCH model, risk prediction errors equal $(e_t)^2 - (\sigma_t)^2$, the difference between the realized squared deviation from the expectation and the expectation of this squared deviation. This "cool" mathematical quantity is tracked in AI, a key region of the "affective brain," suggesting that mathematics is encoded through changes in emotions.

**BOX 2** | Non-invasive brain imaging techniques.

There exist many techniques to "read" neural activation without physically going into the brain. One of the most popular (but expensive) is *functional Magnetic Resonance Imaging* (fMRI), which indirectly, and with a delay, picks up neural activation by tracking oxygen-rich blood that flows to clusters of neurons that have "fired." The fMRI scanner creates a very strong magnetic field, which it disturbs, resonating with oxygen atoms. By recording the resonance, the scanner can identify time and location of the oxygen.

There are many other ways to detect neural activation, such as EEG (Electro-Encephalogram). Recently neuroscientists have come to realize that there are effective and simple ways to track firing by specific clusters of neurons. One cluster is LC, where noradrenergic neurons are located. Firing in that cluster has an effect on *pupil dilation*, and as such, pupil dilations constitute a "mirror" of LC activation, provided of course there are no other reasons for the pupil dilation, such as changes in luminosity (Joshi et al., 2016).

passing through the brain, causing heartbeat modulations. In this sense, changes in heartbeat too could be conceived as indirect measurement of noradrenergic activity, just like pupil dilation.

Despite their far-reaching projections, noradrenergic neurons are unlikely to be the source of complex behaviors or emotions on their own, since the regions whence they originate are tiny and there are too few of these neurons. To understand complex behaviors we have to look to the cortex.

The anterior insula (AI) is a cortical structure in humans (as well as in primates and many other species such as dolphins and whales) which is thought to be responsible for translating emotions – which we define to be bodily reactions as measured in psychophysiology, such as heartbeat, transpiration, blood pressure, etc. – into feelings. Indeed, through AI we become aware of our emotions (Craig, 2014). Not surprisingly, AI activates in reaction to pain and disgust, but also to empathy, effectively "simulating" the emotional reactions of others (Singer et al., 2004) (see also **Box 4**).

With hindsight, it is therefore not surprising that AI is involved in risk tracking as well. In a visual version of the same

**BOX 3** | Neurons and neurotransmitters.

Information processing in the brain is done by a certain type of cell called *neuron*. The neuron receives signals from upstream neurons through many of its *dendrites* ("roots") and collects those signals in the form of electrically charged molecules (ions) into its cell body. Together, cell bodies form the "gray matter" of the brain. If the information carried by those ions is sufficiently strong, the neuron "fires" by sending a charge through its *axon* to downstream neurons it has connected with. As such, neuronal signals are basically binary: to fire or not; like the transistors in a modern electronic computer. The neuron does not physically connect to its downstream neurons. Instead, there is a *synaptic cleft* into which the neuron, if it fires, releases chemicals called *neurotransmitters*, which the downstream neurons will pick up – unless inhibited somehow, e.g., through drugs that neutralize receptors on the downstream neuron. The brain uses many types of neurotransmitters. Some of them don't merely "send information," but rather modulate information transmission, enhancing or reducing the impact of neural signals. E.g., dopamine, serotonin, norepinephrine (or noradrenaline), acetylcholine. Neuropharmacology in general attempts to affect information transmission in the brain by targeting specific neurotransmitters, directly (e.g., inhibiting their re-uptake out of the synaptic cleft; e.g., Prozac), or indirectly (increasing the sensitivity of the receptors of the downstream neurons; e.g., reboxitine).

**BOX 4** | Anterior Insula.

Anterior Insula (AI) is a widely connected cortical structure generally understood to integrate information from various sources, thereby providing a meeting point for sensory, autonomous, affective and cognitive inputs into decision-making. The integrative role of AI explains why activation can simultaneously correlate with bodily phenomena such as pain or disgust and reflect complex mathematical quantities such as risk prediction errors (see **Box 4**). AI also plays a crucial role in self-awareness, enhanced during ecstatic epileptic seizures, which are thought to be caused by a brain network centered around AI. Together with Anterior Cingulate Cortex, the human AI contains peculiar neurons, von Economo neurons, distinguished by their simple dendritic structure (Butti et al., 2013). It is thought that these neurons allow for fast adaptation in an uncertain environment that continuously generates novel circumstances, bypassing the intricate neural network structure of regular, pyramidal neurons. Selective activation of AI under leptokurtic noise, a type of risk that is associated with modern financial markets, but not the traditional, natural environment humans had to navigate, could be one example of how AI specializes in dealing with challenging novel situations.

card game used in the pupil dilation study, we discovered that AI activation correlated with risk anticipation *as well as risk prediction errors* (Preuschoff et al., 2008) (see **Figure 3A**). The study was the first to discover cool, rational mathematical signals in a brain structure that had been associated with emotions, feelings, and awareness, phenomena that were thought to defy formal analysis. It was also one of the key pieces of mounting evidence that emotions were an integral part of rational calculations, thereby casting serious doubt on the widespread belief that the affection (emotions) and cognition (reason) were antagonistic (We will return to this antagonism later.).

The above findings served to finally make sense of a much earlier study. That study was the first to monitor, on the job, the psychophysiology of professional traders, in to contrast to amateurs. Way before the link between outliers, LC and AI was established, it was indeed shown that professional traders reacted emotionally in a very narrow way to participation in financial markets; significant correlation only emerged between changes in heartbeat and *changes in market volatility* (Lo and Repin, 2002).

More evidence has been piling up in recent years. For instance, Payzan-LeNestour et al. (2013) showed direct evidence between LC activation and outliers in a study where outliers were generated differently, namely, through shifts in the mean of the payoff distribution; Nassar et al. (2012) showed that such outliers also drove pupil dilation; AI was found to be engaged in differentiating between frequent outliers that reverted (leptokurtic noise) and outliers that did not (D'Acremont and Bossaerts, 2016).

AI, through its interaction with the heart, thus emerged as the crucial brain structure involved in tracking the very essence of financial risks, namely, leptokurtosis. It turns out that something important was already known about the link between heartbeat changes and AI. Let us now discuss this particular neurophysiological interaction.

## SIZE OF ANTERIOR INSULA CORRELATES WITH HEARTBEAT DETECTION ACCURACY

In 2004, one of the authors of the study of the intero-ceptive capability of professional traders, collaborated on a study of the link between one's ability to sense heartbeat and the size of the AI. The results were reported in Critchley et al. (2004). There, the size of AI was found to correlate with differences in accuracy in determining one's heartbeat.

This study provides the missing link between the aforementioned studies on the role of AI in tracking financial risks and the link between heartbeat sensing and trader performance. To put it all together: the better the connectivity between heart and AI, the better one's senses are "in tune" with changes in financial risks, and hence, the better trader one becomes.

Again, there is no causality meant. It is not clear whether the increased size of AI in better "heartbeat trackers" is its cause or its consequence. The evidence merely points to a strong link in the system financial risk/LC/heartbeat/AI and trading performance. Without the rich neurobiological evidence, however, the correlation between ability to sense heartbeat and trading success could as well have been a fluke. The evidence from the earlier neurobiology studies is consistent with, and provides foundation to, this extraordinary discovery, supporting its credibility.

As the evidence converged, researchers were left with the question of whether any of these physiological signals could be used to predict or drive behavior in complex financial markets. They could, as we explain next.

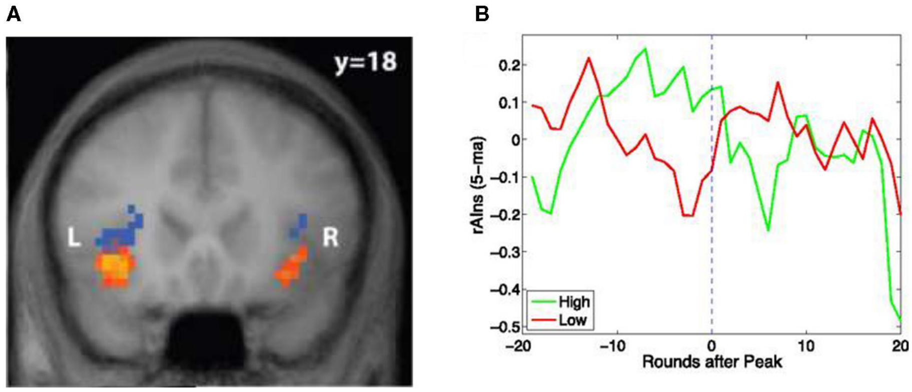


**FIGURE 3 |** Blue regions predict the size of rewards or losses, i.e., the risk. Orange regions track the prediction mistake. Mistakes happen when the size of the actual reward or loss is much bigger than anticipated, i.e., upon an outlier. The regions form part of the Anterior Insula (AI). Based on functional magnetic resonance imaging of brain activation during a card game where the predicted size of reward or losses changes constantly. **(B)** Activation in the region within right AI (rAIns) predicts which traders correctly anticipate the bursting of a financial bubble. Shown is the evolution of activation in the red region next to "R" in **(A)** before and after the trading round when the bubble peaked. Red line is for participants who anticipated that the bubble would have lasted longer. Green line is for participants who correctly anticipated the crash. Sources: **(A)** Preuschoff et al. (2008) and **(B)** Smith et al. (2014).

## MORE ON ANTERIOR INSULA: HOW TO GET OUT OF A BUBBLE IN TIME

AI had been taking a central position in studies of financial decision-making as its activation had been consistently linked to risk and outliers in controlled experiments. As such, it appeared to be a prime candidate for tracking and driving behavior in more complex settings, such as trade in financial markets.

In one experiment, participants traded in an online market setting that is known to generate bubbles – prices that are far above fundamental values in the sense that they are higher than even the sum total of dividends that will ever be paid until the end of the experiment. Some traders participated from inside a scanner. This meant that they could submit orders and trade while their brain activity was being recorded using functional magnetic resonance imaging (fMRI). A number of participants "rode" the bubble: they bought when the security was clearly over-priced, presumably hoping that they would be able to sell in time, before the bubble burst.

Remarkably, this study, Smith et al. (2014), showed that brain activation in AI could be used to predict who would get out in time. They tracked brain activation in the same part of AI where Preuschoff et al. (2008) discovered neural signals correlating with risk prediction errors (see above). Participants with significantly higher AI activation during emergence of the bubble managed to get out in time, thus performing much better than those with lower AI activation (see **Figure 3B**).

Neuroscientists associate AI with emotions, feelings and self-awareness. The crucial role that AI appears to be playing in successfully dealing with financial risks may therefore lead one to conjecture that emotions are an integral part of sound financial decision-making. As it turns out, this link between emotions and financial decision-making had already been made in the 90s, by two neurologists.

## EMOTIONS ARE A NECESSARY CONDITION FOR SOUND FINANCIAL DECISION-MAKING

In the 90s, neurologists noticed that patients with certain lesions in the orbitofrontal cortex (OFC) appeared to make worse financial decisions after they acquired these lesions. OFC is large region that borders on AI, and brain lesions tend to be diffuse, which means that if they affected OFC, they were likely to impact borderline regions as well. The neurologists set out to test their patients' ability to choose rationally by means of controlled experiments.

The task they gave their patients, the *Iowa Gambling Task*, is effectively a four-armed bandit problem in the form of a card game. Unbeknown to the participants, two arms dominated, in the sense that they generated payoffs that were better both in terms of expected payoff (positive rather than negative) and in terms of risk (variance and range of payoffs). Against healthy controls, patients continued to choose the bad arms long after it should have become clear that they were dominated, and even though they expressed awareness of their higher risks and lower returns.

Significantly, the neurologists discovered that their patients had no emotional anticipation of the risks they were taking (Bechara et al., 1997). In particular, unlike healthy controls, they did not exhibit anticipatory anxiety, in the form of transpiration (measured by changes in skin conductance) when choosing the inferior, high-risk arms.

This amounted to the first evidence, in the context of finance, that the traditional picture of a tension between affection (emotions) and cognition (reason) was wrong. Yet the view that emotions stand in the way of rational decision-making is still widely promoted in economics and psychology. To counter this, in an article in a 2005 issue of *Games and Economic Behavior*, the aforementioned neurologists emphasized that "[e]merging neuroscience evidence suggest that sound and rational decision-making, in fact, depends on prior accurate emotional processing" (Bechara and Damasio, 2005).

The importance of emotions in reasoned decision-making is a recurring theme in decision neuroscience. In 2017, neuroscientists discovered that higher susceptibility to losses than to gains ("loss aversion") is *not* the result of increased activation of emotional neural circuits, but of reduced overall task engagement. In one sense, they actually found the contrary: *choices became more rational upon increased engagement of both emotional and affective brain circuitries* (Li et al., 2017).

## IN SUMMARY

At first, the findings from the *Scientific Reports* article of a correlation between the ability to track reliably one's heartbeat and performance of professional traders in financial markets seem odd. Without further evidence one might have been tempted to dismiss them as spurious, certainly in view of the small sample size, and unlikely to be replicable. Yet, not only did further evidence exist, it explained why the correlation emerged.

Emotions are an integral part of rational decision-making. As such, a trader who cannot sense own heartbeat is at risk to underperform, and not to last long on the job. This does not mean that emotions are good *per se*. In 2012, Fenton-O'Creevy et al. (2012) provided a qualitative investigation of how antecedent-focused heartrate regulation improved trading performance, but response-focused regulation did not. Recently, Bossaerts et al. (2020) confirmed the finding quantitatively, using the same experimental paradigm as in Smith et al. (2014).

In view of these and other findings we argue that the claim that emotions "have not been incorporated into the economic theory of decision-making under uncertainty" [p. 55, Caplin and Leahy (2001)] is no longer tenable: if emotions contribute to maximizing utility, then somehow they are an integral part of rational decision-making. Where exactly they show up in the mathematics is yet to be determined in detail, and will require collaboration between economists and neuroscientists, in the tradition of neuroeconomics.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://academic.oup.com/cercor/article/26/4/1818/2367610#supplementary-data.

## AUTHOR CONTRIBUTIONS

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# Are People Altruistic When Making Socially Responsible Investments? Evidence From a tDCS Study

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Socially responsible investment (SRI) is an emerging philosophy that integrates social and environmental impacts into investment considerations, and it has gradually developed into an important form of investment. Previous studies have shown that both financial and non-financial motivations account for SRI behaviors, but it is unclear whether the non-financial motive to adopt SRI derives from investors' altruism. This study uses neuroscientific techniques to explore the role of altruism in SRI decision-making. Given that existing evidence has supported the involvement of the right temporoparietal junction (rTPJ) in altruism and altruistic behaviors, we used transcranial direct current stimulation (tDCS) to temporarily modulate activity in the rTPJ and tested its effect on charitable donations and SRI behaviors. We found that anodal stimulation increased the subjects' donations, while cathodal stimulation decreased them, suggesting that tDCS changed the subjects' levels of altruism. More importantly, anodal stimulation enhanced the subjects' willingness to make SRIs, while cathodal stimulation did not have a significant impact. These findings indicate that altruism plays an important role in SRI decision-making. Furthermore, cathodal stimulation changed the subjects' perceived effectiveness of charitable donation but not that of socially responsible fund. This result may help explain the inconsistent effects of cathodal stimulation on charitable donations and SRI behaviors. The main contribution of our study lies in its pioneering application of tDCS to conduct research on SRI behaviors and provision of neuroscientific evidence regarding the role of altruism in SRI decision-making.

**Keywords: socially responsible investment, altruism, motivation, right temporoparietal junction, transcranial direct current stimulation**

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## INTRODUCTION

Socially responsible investment (SRI) is an investment discipline that adds concerns about social or environmental issues as a determinant of investment portfolio construction or investment activities in the consideration of investment risks and returns (Sparkes and Cowton, 2004; Sparkes, 2008). As an emerging investment philosophy, SRI has been favored by an increasing number of investors in recent years, and it has gradually developed into an important form of investment

(Eurosif, 2020). Notably, SRI has expanded rapidly throughout the COVID-19 pandemic. For instance, in the second quarter of 2020, global sustainable fund inflows increased by 72%, with assets under management exceeding US$1 trillion for the first time (Morningstar, 2020). Therefore, it is important to better understand SRI behaviors and, in particular, the psychological motivations of SRI investors.

Studies have explored the motivations behind SRI. Some studies show that SRI is driven by financial motives for higher returns or lower risks. For instance, Jansson and Biel (2011) found that the main motivation for investors to engage in SRI lies in a belief that socially responsible assets can bring higher investment returns. From a questionnaire survey, Glac (2009) found that when making investment decisions, financial considerations are usually more prominent than social considerations; thus, investors are usually unwilling to sacrifice financial returns to follow their beliefs. Døskeland and Pedersen (2016) and Riedl and Smeets (2017) noted that once investors perceive the expected returns from socially responsible assets to be poor or lower than those from traditional assets, their willingness to make SRIs will decrease. In addition, people believe that socially responsible companies usually face fewer reputational and litigation risks or that, at the very least, they will achieve less risk under the same financial benefits (Beal et al., 2005; Renneboog et al., 2008). From a questionnaire survey, Dorfleitner and Utz (2014) found that expectations of returns and risks significantly affect investors' SRI behaviors and willingness to sacrifice returns. Empirical studies have also found that the financial performance of portfolios with high levels of social responsibility is generally better with regard to returns and risks (Orlitzky and Benjamin, 2001; Derwall et al., 2004).

Other studies have provided evidence that SRI is also driven by non-financial motives, which are believed to derive from considerations of the impact of investment decisions on social interests. Lewis and Mackenzie (2000) found that investors generally face a dilemma between pursuing morality and pursuing their financial interests. Statman (2004) and Nilsson (2009) found that investors show significant individual differences in their evaluations of financial returns and social responsibility; investors with high levels of social responsibility are willing to sacrifice more financial returns for their own moral pursuits. Hartzmark and Sussman (2019) observed investment decisions on traditional assets and socially responsible assets at different return levels and found that investors are willing to sacrifice their own investment returns for SRIs. Bonnefon et al. (2019) found that the prosocial preferences of investors are positively correlated with SRI behavior. Wins and Zwergel (2016) and Brodback et al. (2019) used questionnaires to study the personal values of investors and found that their altruistic values significantly impact their SRI behaviors. In particular, when investors believe that their investment behaviors can play a positive role in society, they will be more willing to make SRIs.

Many of the above studies finding that SRI is partly driven by non-financial motives attributed these motives or directly refer to such motives as prosocial preferences, or more specifically, altruism. Theories of prosocial preferences are based on the notion that people care about the well-being of others (Charness and Rabin, 2002; Meier, 2007). A crucial type of prosocial preference is altruism, and being altruistic means that a person's utility increases with the well-being of other people (Fehr and Schmidt, 2006). Nevertheless, some other factors may also account for investors' non-financial motives observed in the real world, such as those of reputational concern and social conformity. Even in an experimental environment, subjects may also unconsciously integrate their real-world experiences into investment tasks. Therefore, more evidence is needed regarding whether altruism plays an important role in SRI decision-making.

Our study uses neuroscientific methods to explore the role of altruism in SRI decision-making. Previous neuroscientific studies have found that the temporoparietal junction (TPJ) plays a key role in altruism and altruistic behaviors. Some studies have found that enhancing activity in the TPJ will increase the empathy and altruistic behaviors of individuals (Jeurissen et al., 2014; van der Meulen et al., 2016). Other studies have found that subjects who are willing to allocate more money to others in a dictator game show stronger activity in their TPJ, especially in the right temporoparietal junction (rTPJ) (Hutcherson et al., 2015; Strombach et al., 2015; Park et al., 2017). Recent studies have also used closer-to-life altruistic tasks to measure subjects' altruistic preferences by asking them to allocate funds to themselves or charities. Hare et al. (2010) and Tusche et al. (2016) found that subjects who donated more to charities showed higher activity in the rTPJ. Using transcranial direct current stimulation (tDCS), Li et al. (2020) found that those who received anodal stimulation increased their donations to charities.

Evidence also indicates that the functional contribution of the rTPJ to altruism lies in signaling conflicts between moral and material interests. Morishima et al. (2012) found that activity in the rTPJ depends on the cost of altruistic behavior. When the cost of altruism is low, activity in the rTPJ is positively correlated with altruistic behavior. However, when self-interested behavior conflicts with altruistic behavior, this will lead to a decrease in activity in the rTPJ. Obeso et al. (2018) further showed that the rTPJ is involved in handling moral-material conflicts involved in donation behavior. After disrupting the rTPJ using transcranial magnetic stimulation, subjects showed reduced monetary self-interest and donated significantly more than the control group.

This study used tDCS to temporarily modulate activity in the rTPJ and tested how different stimulation modes affected subjects' donation and SRI behaviors. Based on existing evidence, our hypotheses are as follows. First, modulating activity in the rTPJ using tDCS will alter subjects' processing of moral-material conflicts, thus changing subjects' donation behaviors. Second and more importantly, if altruism does play an important role in SRI decision-making, then changes in subjects' processing of moral-material conflicts will also lead to changes in their SRI behaviors. More specifically, we hypothesize that increasing activity in the rTPJ will increase subjects' donation and SRI behaviors, while decreasing activity in the right rTPJ will decrease their donation and SRI behaviors. By modulating activity in the rTPJ, we tried to disentangle the motive of altruism and other possible non-financial motives and to see if the process of SRI decision-making does involve altruistic considerations.

# MATERIALS AND METHODS

## Subjects

A total of 96 subjects (24 males and 72 females; mean age: 21.23 years, ranging from 18 to 28 years) were recruited to participate in our experiment. All of the subjects were students at Shanghai International Studies University, and they were randomly assigned to receive anodal ($n$ = 32; males: 8, females: 24; mean age: 21.21), cathodal ($n$ = 32; males: 8, females: 24; mean age: 21.21), or sham stimulation ($n$ = 32; males: 8, females: 24; mean age: 21.25). All subjects were right-handed, and all of them reported having no history of mental illness or neurological disease and having no experience with tDCS or investment tasks. Before participating in the experiment, the subjects were required to sign a written informed consent form to receive tDCS. The experiment was conducted in the Key Laboratory of Applied Brain and Cognitive Sciences of Shanghai International Studies University, and the experimental scheme was approved by the ethics committee of the laboratory. The whole experiment lasted approximately 1 h, and the subjects received, on average, 60 RMB yuan (approximately $9.17) as compensation. No side effects, such as scalp pain or headache, were reported after the experiment.

## Transcranial Direct Current Stimulation

Transcranial direct current stimulation (tDCS) is a non-invasive form of brain stimulation technology. The stimulation equipment used was developed by Soterix Medical Inc. (New York, United States) and used two saline-soaked sponge electrodes (size: 5 cm × 7 cm) to generate a weak current in the target brain area of the subjects. **Figure 1** shows how the electrodes were placed under anodal stimulation conditions. According to the International 10/20 EEG Positioning System (Jasper, 1958), we aimed to place the center of the anodal electrode over CP6 (Jurcak et al., 2007; Koessler et al., 2009), and the cathodal electrode was placed on the subject's opposite (left) cheek (Berryhill and Jones, 2012; Tseng et al., 2012; Mai et al., 2016). Under cathodal stimulation conditions, we aimed to place the center of the cathodal electrode over CP6, and the anodal electrode was placed on the subject's left

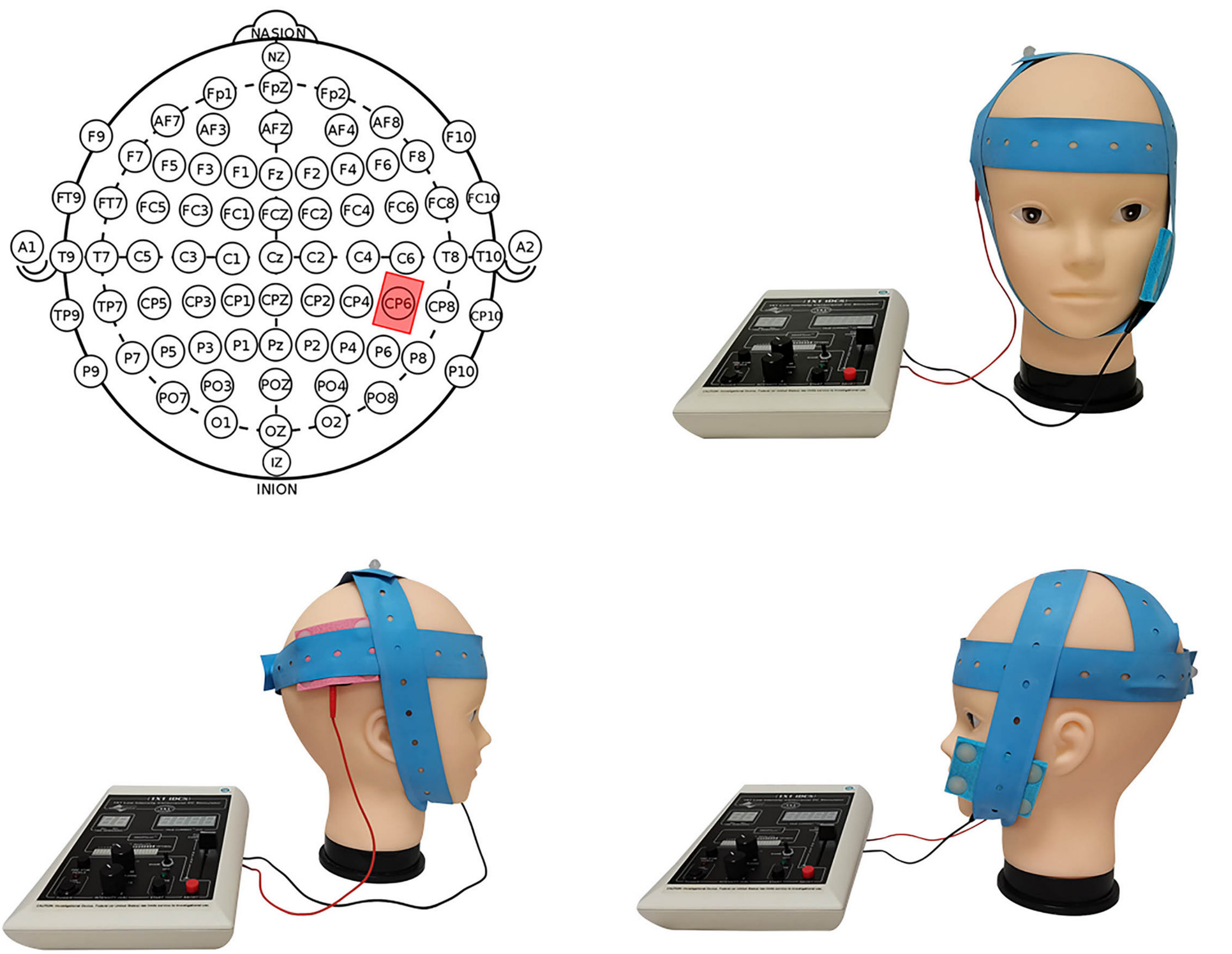


**FIGURE 1 |** Schematic and locations of the electrodes applied under the anodal stimulation mode.

cheek. The sham stimulation conditions randomly adopted the electrode placement of either anodal or cathodal stimulation. The stimulation delivered a constant current of 1.5 mA lasting 20 min to induce changes in the excitability of the cerebral cortex of the target area without causing any physiological harm to the subjects. According to previous studies, the anodal electrode enhances the excitability of the cortex, and the cathodal electrode inhibits the excitability of the cortex (Nitsche and Paulus, 2000). For sham stimulation, the current was delivered for only 30 s, and this method has been proven reliable by previous studies (Gandiga et al., 2006).

## Experimental Design

Our experiment involved the following four tasks performed in fixed order: a charity donation task, simulated SRI task, real SRI task, and risk preference measurement task. Each of the first three tasks was set up with a "personal wallet" and a "charity wallet." The personal wallet contained the payoffs received by the subject from the task, and the charity wallet contained the charitable donation generated by the task. We chose the Alipay charitable platform as the recipient of the donations since this platform covers a wide range of charity projects (i.e., education assistance, poverty alleviation, disaster relief, medical assistance, and environmental protection) and is held in high esteem in China. Anyone can make online donations easily on this platform through electronic payments.

### Donation Task

The donation task is a modified version of the dictator game that is usually used to test altruism (Forsythe et al., 1994; Eckel and Grossman, 1996). In the task, the subjects were given a sum of 50 yuan and had to decide how much to donate to charity. The amount donated to charity was transferred to the charity wallet, and the remaining amount was allocated to the subject's personal wallet. The more money the subject donated to charity, the higher his/her level of altruism was.

### Simulated SRI Task

The simulated SRI task was designed based on Bonnefon et al. (2019) and Brodback et al. (2020), and we integrated and modified their tasks to the purposes of our research. In our task, the subjects were given 50 yuan and were asked to make bids for an ordinary asset and a socially responsible asset. Both assets had a 50% probability of yielding a return of 40 yuan and a 50% probability of yielding only 10 yuan for the subject's personal wallet. However, the socially responsible asset would also donate an additional 10 yuan to charity (with the amount in the charity wallet increasing by 10 yuan without changing the amount in the personal wallet) if it was purchased. The subjects were asked to report the highest prices they were willing to pay for the two assets (minimum: 0, maximum: 50). The subjects only made two decisions for this task: a bid for the ordinary asset and then a bid for the socially responsible asset with a fixed order. To avoid the wealth effect, the computer randomly selected one asset to provide payment for this task. To incentivize the subjects to disclose their real evaluations of the assets, we adopted the Becker-DeGroot-Marschak (BDM) bidding mechanism of Becker et al. (1964). This mechanism can ensure that for a rational subject, the optimal choice is to report his/her true willingness to pay. The operation of the mechanism was set as follows: The asset price was randomly generated in the interval of [0,50]. If the subject's bid was lower than the random price, the asset could not be purchased. If the subject's bid was equal to or higher than the random price, the asset would be successfully purchased at the random price. Based on the design of the task, a higher bid could be regarded as a greater willingness to invest in the asset. In addition, we could offset the impact of financial motives by calculating the differences between the subjects' bids for the socially responsible asset and the ordinary asset since both assets have the same levels of risks and returns. In other words, the difference between the bids for the two assets could reflect the subjects' non-financial motives to engage in SRI.

### Real SRI Task

The real SRI task involved investment decision-making with regard to a real socially responsible fund. For the task, the subjects were given 50 yuan and were asked to make a bid (minimum: 0, maximum: 50) for a real socially responsible fund, the Xingquan Social Responsibility Mix Fund. This fund is a publicly offered socially responsible fund in China. While pursuing returns, the fund also emphasizes the performance of listed companies in terms of sustainable development, law, and moral responsibility. The fund can be easily purchased and sold through a mobile app, and the minimum capital requirement is as low as 10 yuan. To incentivize the subjects to disclose their real evaluations of the fund, the task also applied the BDM bidding mechanism, as in the simulated SRI task. If the subject's bid was equal to or higher than the randomly generated price, the investment was successful, and a real share of the fund worth 50 yuan (at that moment) could be obtained at the generated random price. The experimenter helped the subjects purchase the corresponding share of the fund through the app on their own mobile phones when the experiment was over. If the subject's bid was lower than the randomly generated price, the fund was not bought, and the subject retained 50 RMB yuan. Similarly, the subject's bid for the fund reflected his/her willingness to invest in real socially responsible funds.

### Risk Preference Measurement Task

Risk preference plays an important role in investment decision-making. Therefore, we also measured the subjects' risk preferences to explore whether the effects of stimulation modes on subjects' investment behaviors were due to changes in their risk preferences. The risk preference measurement task followed the method of Falk et al. (2018) to assess the subjects' risk preferences. The task consisted of two parts. For the first part, the subjects were asked to rate their own preference for risk on a 10-point scale (i.e., self-rated risk level). The second part involved 5 multiple-choice questions on risk drawn from a pool of 31 multiple-choice questions. Each question in the question bank had two options, A and B, where A was "50% likely to receive 300 yuan, 50% likely to receive 0 yuan" and B was "a fixed reward of X yuan" (where X changes in different questions). For each question displayed, the subjects needed to choose the preferred option, and their choices determined the value of X included in the next question displayed. A staircase risk level could be obtained based on the subjects' answers to the 5 questions. Based on the results of the two parts, each subject's level of risk preference could be calculated.

## Experimental Procedure

The experimental tasks were programmed and implemented using oTree software (Chen et al., 2016). At the beginning of the experiment, the subjects were given tDCS for 20 min, during which time they rested in a chair. When the stimulation was over, the devices were removed from the subjects' heads. Then, the subjects were asked to perform the four tasks described above in sequence (**Figure 2**) and were told that at the end of the experiment, the computer would randomly select one of the first three tasks to execute the payment of the experiment (including the subjects' payoffs and charity donations). In addition, to be consistent with the risk preference measurement task of Falk et al. (2018), we did not pay for this task. After all tasks were completed, the subjects were asked to complete a questionnaire on some control factors such as the perceived effectiveness of charity donation (the extent to which the subjects believe that charity donations can have a positive impact on society); the perceived effectiveness of socially responsible fund (the extent to which the subjects believed that investing in socially responsible funds could have a positive impact on society); the subjects' return and risk performance evaluations of the Xingquan Social Responsibility Mix Fund; and the subjects' demographic characteristics in terms of gender, age, educational level, and family income level. Then, the computer randomly chose one of the first three tasks to implement payment for the whole experiment, and only when the simulated or real SRI task was chosen was the random price generated. In other words, the subjects did not know their final payoff until the end of the experiment. The subjects generally took approximately 20 min to complete all of the poststimulation tasks. Finally, the subjects received their payoffs and witnessed the online charity donation executed by the experimenter.

# RESULTS

## Effects of tDCS

**Figure 3** summarizes the statistical characteristics of the data obtained from each task under different stimulation modes. We first conducted a one-way ANOVA to test the impact of different stimulation modes on the data for each task. We report the Bonferroni correction results for pairwise comparisons and set the standard for significance at 0.05. Outliers were kept in the analyses because we think that each decision was made by its own logic in our experiment, and it is inappropriate to remove a decision simply because it considerably different from others. Nevertheless, we also ran analyses without outliers, and the conclusions are the same.

To test whether the stimulations changed the subjects' altruistic preferences, we compared the donation amounts of subjects in different stimulation groups for the donation task and found significant differences ($F_{2,93}$ = 14.913, $p$ < 0.001). Among them, the average donation of the subjects under anodal stimulation was significantly higher than that under sham stimulation (mean: anodal = 20.44, sham = 13.31, $p$ = 0.01). Compared to the subjects in the sham stimulation group, the subjects in the cathodal stimulation group were significantly less willing to donate (mean: cathodal = 7.41, sham = 13.31; $p$ = 0.046). These results demonstrate that

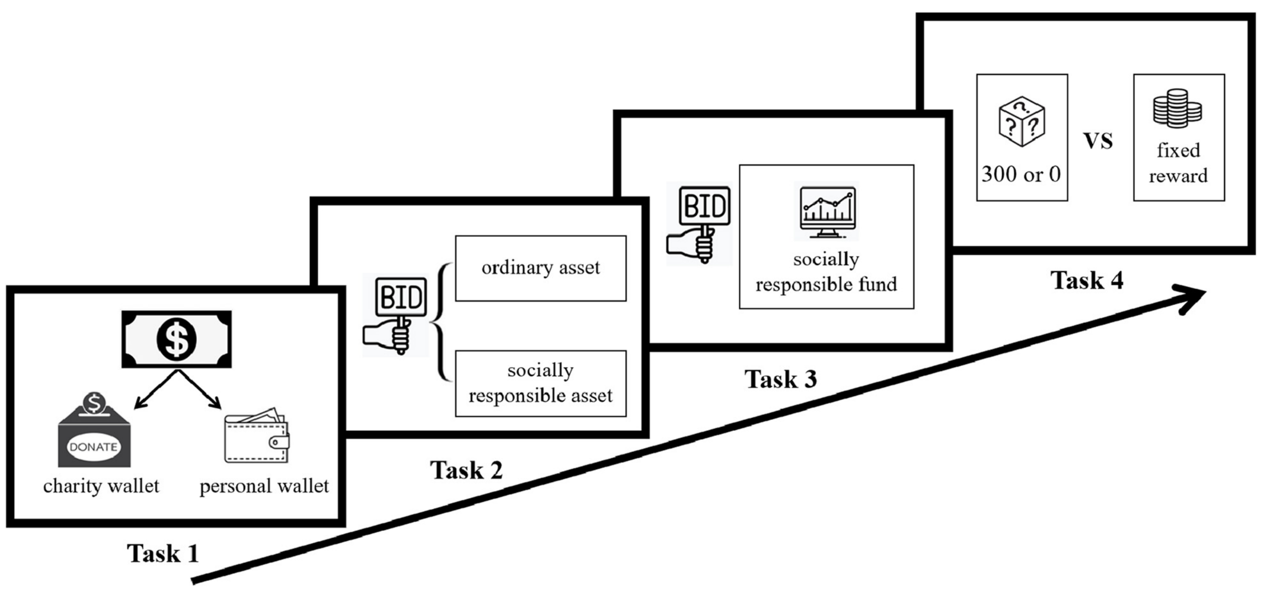


**FIGURE 2 |** The four sequential tasks of the experiment. The subjects were asked to complete the charity donation, simulated SRI, real SRI, and risk preference measurement tasks in a fixed order. The subjects generally took approximately 20 min to finish all of these tasks.

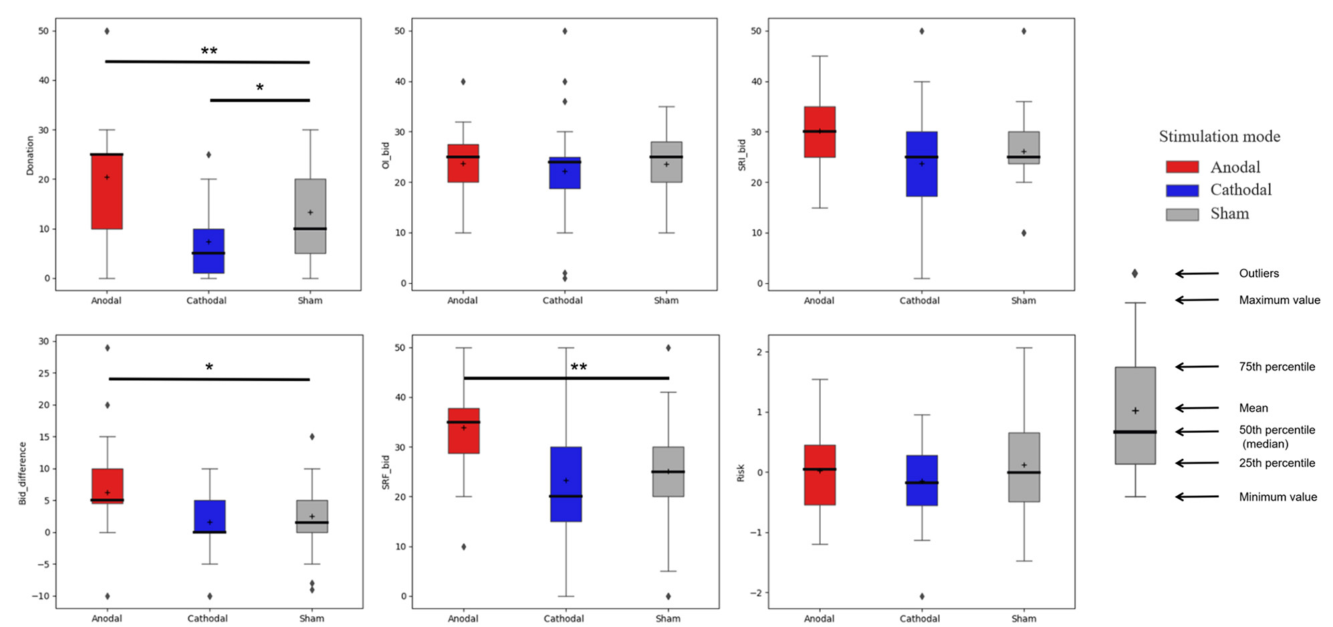


**FIGURE 3 |** Statistical characteristics of the variables used for each task under different stimulation modes. *Donation* represents the donation amounts given by the subjects for the donation task. *OI_bid* and *SRI_bid* represent the subjects' bids for the ordinary asset and socially responsible asset, respectively, and *Bid_difference* represents the difference in the subjects' bids for the two assets (*SRI_bid-OI_bid*) for the simulated SRI task. *SRF_bid* represents the subjects' bids for the socially responsible fund for the real SRI task. *Risk* represents the subjects' risk preferences under the risk preference measurement task, where the smaller the value is, the less risk-seeking the subject is. Asterisks indicate significant differences (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

we successfully changed the subjects' levels of altruism. The results are also consistent with the conclusions of previous studies showing that activity in the rTPJ is positively correlated with the level of altruism (Morishima et al., 2012; Hutcherson et al., 2015; Strombach et al., 2015). In addition, we found a significant effect of stimulation modes on the subjects' perceived effectiveness of charity donation ($F_{2,93}$ = 5.102, $p$ = 0.008), which was used to measure the extent to which the subjects believed that charity donations could have a positive impact on society. Pairwise comparisons show that cathodal stimulation significantly decreased the subjects' perceived effectiveness of charity donation, while anodal stimulation did not change it (mean: anodal = 4.47, cathodal = 4.09, sham = 4.53; anodal vs. sham: $p$ = 1.000; cathodal vs. sham: $p$ = 0.012).

Upon analyzing the asset bids of the subjects for the simulated SRI task, we found, overall, no significant differences in the ordinary asset bids under different stimulation conditions ($F_{2,93}$ = 0.405, $p$ = 0.668). This result indicates that the stimulations did not affect the subjects' financial motives or willingness to invest in the ordinary asset. In contrast, we found a significant difference in the bids for the socially responsible asset under different stimulation modes ($F_{2,93}$ = 4.571, $p$ = 0.01). The average bid made under anodal and cathodal stimulation conditions was not significantly different from that made under sham stimulation conditions (mean: anodal = 30.16, cathodal = 23.72, sham = 26.13; anodal vs. sham: $p$ = 0.192; cathodal vs. sham: $p$ = 0.799). Nevertheless, the average bid made in the cathodal stimulation group was significantly lower than that made in the anodal stimulation group ($p$ = 0.01). These results preliminarily indicate that the stimulations may have changed the subjects' evaluations of SRI, but more evidence must be provided.

To further eliminate the impact of financial motives, we subtracted each subject's ordinary asset bid from his/her socially responsible asset bid, denoting the difference as *Bid_difference*. This variable indicates the strength of the subject's non-financial motive to engage in SRI. We found significant differences in the *Bid_difference* values of the subjects under different stimulation conditions ($F_{2,93}$ = 6.366, $p$ = 0.003). The average *Bid_difference* of the anodal stimulation group was significantly higher than values for the sham and cathodal stimulation groups (mean: anodal = 6.28, cathodal = 1.59, sham = 2.50; anodal vs. sham: $p$ = 0.024; anodal vs. cathodal: $p$ = 0.003). However, no significant difference was found between the average *Bid_difference* values of the cathodal and sham stimulation groups ($p$ = 1.000). These results further verify that anodal stimulation but not cathodal stimulation changed the subjects' non-financial motives to engage in SRI.

The subjects' bids for the socially responsible fund for the real SRI task show similar results. We found significant differences in the bids of different stimulation groups ($F_{2,93}$ = 8.853, $p < 0.001$). The average bid for the anodal stimulation group was significantly higher than that for the sham and cathodal stimulation groups (mean: anodal = 33.97, cathodal = 23.28, sham = 25.06; anodal vs. sham: $p$ = 0.004; anodal vs. cathodal: $p < 0.001$). Consistent with the simulated SRI task, although the subjects of the cathodal stimulation group generally offered lower bids than those of the sham stimulation group, the difference was not significant ($p$ = 1.000). Nevertheless, we did not find a significant effect of stimulation modes on the subjects' perceived effectiveness of socially responsible fund ($F_{2,93} = 0.635$, $p = 0.532$), which was used to measure the extent to which the subjects believed that investing in socially responsible funds could have a positive impact on society.

We also compared the risk preferences of the subjects under different stimulation modes to determine whether the stimulations changed their risk preferences. The calculation of the risk preferences was based on Falk et al. (2018). We first standardized the two risk indicators (self-rated risk level and staircase risk level) obtained from the risk preference measurement task and then added them up with different weights ($Risk = 0.4729985 \times$ staircase risk level $+ 0.5270015 \times$ self-rated risk level). We found no significant differences in the *Risk* values of the subjects under different stimulation conditions ($p = 0.36$). This result indicates that the stimulations did not affect the subjects' risk preferences. In other words, the observed effect of stimulation on SRI was not caused by changes in risk preferences.

**Figure 4** further shows the scatter plots and distribution curves of *Donation*, *Bid_difference*, and *SRF_bid* for different stimulation modes. We find that the distributions of these variables are generally consistent with the results of the one-way ANOVAs. The distribution curves of *Donation* for the three

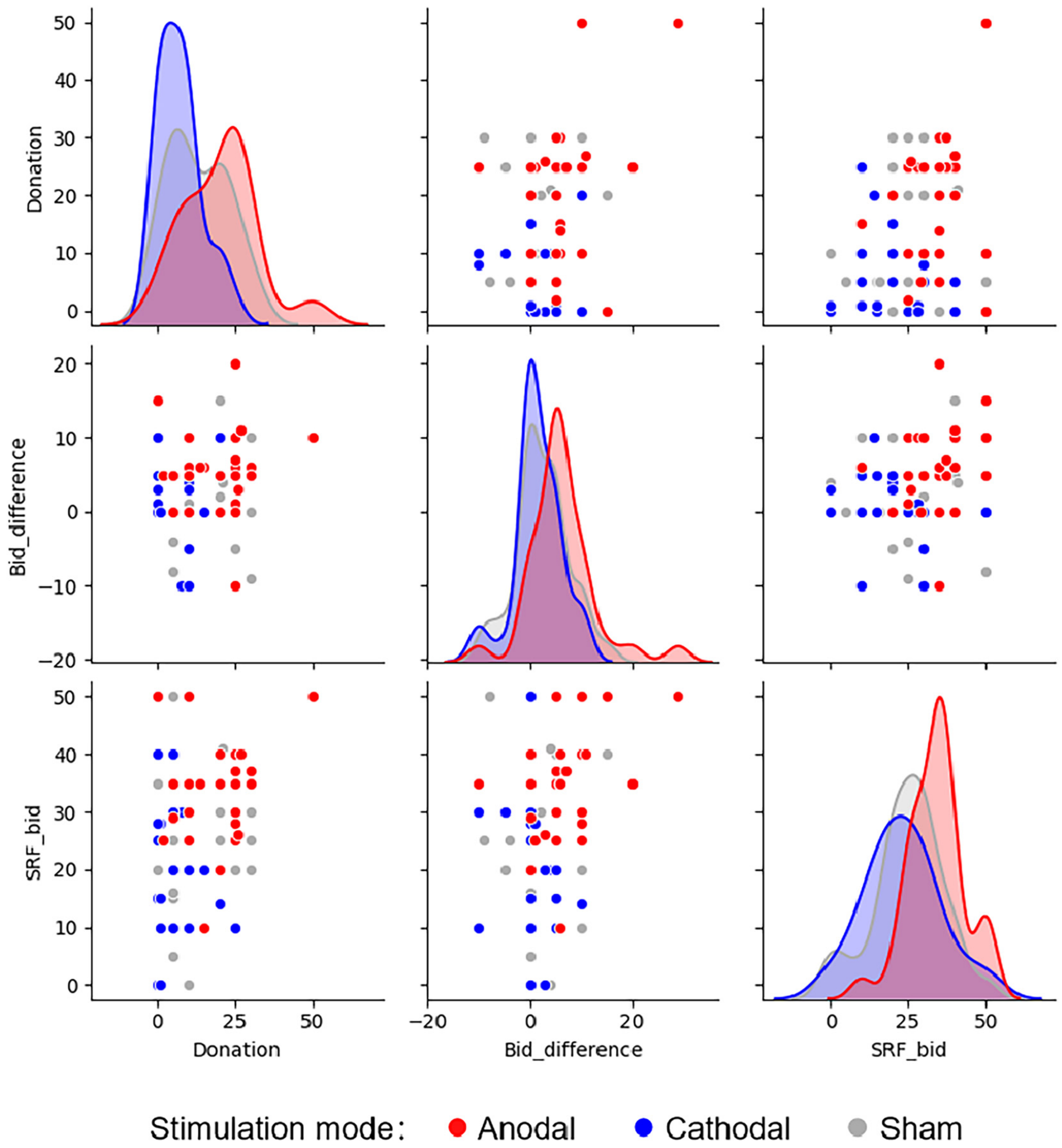


**FIGURE 4 |** Scatter plots and distribution curves of important variables under different stimulation modes. *Donation* represents the donation amounts given by of the subjects for the donation task. *Bid_difference* represents the difference in the subjects' bids for the two assets for the simulated SRI task. *SRF_bid* represents the subjects' bids for the socially responsible fund for the real SRI task. Each dot represents the choice made by one subject.

stimulation groups differ to some extent, indicating that both anodal and cathodal stimulations changed the subjects' levels of altruism. In contrast, the distribution curves of *Bid_difference* and *SRF_bid* for the cathodal and sham stimulations are more similar, showing that only the anodal stimulation changed the subjects' non-financial motives to engage in SRI.

## Robustness Tests

Next, we conducted ANCOVAs to test whether the effects of the stimulations were robust when controlling for other factors. We took the stimulation mode as a fixed factor and other related variables as covariates. The results and parameter estimates are shown in **Table 1**. Again, we report the Bonferroni correction results for pairwise comparisons and set the standard for significance to 0.05. Outliers were also kept in the analyses as described in Section 3.1. We also ran analyses without outliers, and the conclusions were found to be the same.

For the donation task, we took *Donation* as the dependent variable and the perceived effectiveness of charity donation, gender, age, educational level, and income level as covariates (Model 1). After adding the covariates, we still found a significant effect of the stimulation mode ($F_{2,88}$ = 14.880, $p$ < 0.001, $\eta^2$ = 0.253). The donation amount of the anodal stimulation group was significantly higher than the values for the sham ($p$ = 0.02) and cathodal stimulation groups ($p$ < 0.001), while the donation amount of the cathodal stimulation group was significantly lower than that of the sham stimulation group ($p$ = 0.026). Moreover, we still found a significant effect of the stimulation mode on the subjects' perceived effectiveness of charity donation after controlling for gender, age, educational level, and income level ($F_{2,89}$ = 4.886, $p$ = 0.010, $\eta^2$ = 0.099). Cathodal stimulation significantly decreased the subjects' perceived effectiveness of charity donation ($B$ = –0.441, $p$ = 0.005), while anodal stimulation did not change it ($B$ = –0.068, $p$ = 0.658).

For the simulated SRI task, we took the subjects' bids for the ordinary asset as the dependent variable and took risk preferences, gender, age, educational level, and income level as covariates (Model 2). The results show that when the covariates were added, the stimulation mode still had no significant effect on the bid ($F_{2,88}$ = 0.173, $p$ = 0.841, $\eta^2$ = 0.004). However, the impact of risk preferences on the bid was significant ($p$ = 0.008). The more risk-seeking the subject was, the more he/she bid for

**TABLE 1 |** Results of the ANCOVA models and parameter estimates.

| | (1) *Donation* | (2) *OI_bid* | (3) *SRI_bid* | (4) *SRI_bid* | (5) *Bid_difference* | (6) *SRF_bid* | (7) *Risk* |
|---|---|---|---|---|---|---|---|
| *Anodal* | 2.773** (2.46) | 0.044 (1.972) | 2.493* (1.927) | 3.606*** (1.260) | 3.333*** (1.321) | 3.138** (2.547) | –0.309 (0.194) |
| *Cathodal* | –2.686** (2.572) | –0.483 (1.987) | 0.453 (2.020) | 0.468 (1.318) | 0.533 (1.385) | –0.600 (2.572) | –1.121 (0.194) |
| *PCE_donation* | –1.129 (1.708) | | 3.715*** (1.351) | 3.494*** (0.899) | 2.477* (0.926) | | |
| *Risk* | | 2.708** (1.077) | 3.212** (1.062) | | 1.086 (0.728) | 3.547*** (1.367) | |
| *OI_bid* | | | | 11.855*** (0.067) | | | |
| *fund_return* | | | | | | 1.055 (1.614) | |
| *fund_risk* | | | | | | –1.240 (1.379) | |
| *PCE_SRF* | | | | | | 1.428 (1.353) | |
| Gender | –0.189 (2.329) | 0.422 (1.870) | –1.074 (1.826) | –2.127* (1.195) | –2.095* (1.251) | –2.632** (2.383) | 0.387 (0.184) |
| Age | –0.393 (0.794) | –0.548 (0.646) | 0.838 (0.631) | 2.337* (0.407) | 2.041* (0.433) | 0.452 (0.821) | 1.633 (0.063) |
| Education | 0.154 (3.293) | 0.009 (2.650) | –0.691 (2.590) | –1.355 (1.687) | –1.108 (1.775) | –1.362 (3.397) | –0.918 (0.260) |
| Income | 0.350 (0.929) | 0.319 (0.753) | 0.047 (0.736) | –0.167 (0.478) | –0.616 (0.505) | –0.530 (0.959) | 1.379 (0.073) |
| Constant | 1.771 (15.662) | 2.662** (11.213) | –0.348 (12.617) | –2.740** (8.052) | –2.496* (8.648) | 1.319 (16.740) | –1.843 (1.083) |
| $R^2$ | 0.258 | 0.095 | 0.332 | 0.714 | 0.278 | 0.373 | 0.076 |
| Adjusted $R^2$ | 0.198 | 0.023 | 0.271 | 0.688 | 0.211 | 0.299 | 0.014 |
| F | 4.360*** | 1.314 | 5.407*** | 27.195*** | 4.178*** | 5.056*** | 1.228 |
| N | 96 | 96 | 96 | 96 | 96 | 96 | 96 |

*Anodal/Cathodal denotes that the subject received anodal/cathodal stimulation (baseline: sham stimulation). PCE_donation represents the subjects' perceived effectiveness of charity donation. Fund_return and fund_risk represent the subjects' return and risk performance evaluations of the Xingquan Social Responsibility Mix Fund, respectively. PCE_SRF represents the subjects' perceived effectiveness of socially responsible fund. Gender takes a value of 1 for females and a value of 0 for males. Standard errors are shown in parentheses and asterisks indicate significant differences (* 0.05, ** 0.01, *** 0.001).*

the asset. These results further verify that the stimulations did not affect the subjects' financial motives.

When taking the subjects' bids for the socially responsible asset as the dependent variable, we first used risk preferences, the perceived effectiveness of charity donations, gender, age, educational level, and income level as covariates (Model 3). After adding these covariates, we found that the stimulation mode still had a significant impact on the asset bid ($F_{2,87}$ = 3.527, $p$ = 0.034, $\eta^2$ = 0.075). Moreover, compared to those found from the one-way ANOVAs, the differences in the bids of the anodal and sham stimulation groups became more significant (with a decrease in $p$ from 0.192 to 0.044). The cathodal stimulation group did not lower the asset bid relative to the sham stimulation group ($p$ = 1.000), which is consistent with the results of the one-way ANOVAs. The subjects' risk preferences and perceived effectiveness of charity donation also had significant impacts on the bid. The stronger risk preferences and perceived effectiveness were, the higher the bid became *(Risk*: $p$ = 0.002, *PCE_donation*: $p < 0.001$).

Since the bids for the ordinary asset denote the subjects' preferences and considerations of risks and returns, they could also be used as a factor in predicting bids for the socially responsible asset. We used the subjects' bids for the socially responsible asset as the dependent variable and took their bids for the ordinary asset, and the perceived effectiveness of charity donations, gender, age, educational level, and income level as covariates (Model 4). We found that the stimulation mode had a very significant impact on the bids for the socially responsible asset ($F_{2,87}$ = 7.685, $p$ = 0.001, $\eta^2$ = 0.150). The bids of the anodal stimulation group were significantly higher than those of the sham ($p$ = 0.002) and cathodal stimulation groups ($p$ = 0.009). Consistent with the results of the one-way ANOVAs, we found no significant difference between the cathodal and sham stimulation groups ($p$ = 1.000). We also observed that the higher the subjects' bids for the ordinary asset and the higher the degree of the perceived effectiveness of charity donation became, the higher the bids for the socially responsible asset became (*OI_bid*: $p < 0.001$, *PCE_donation*: $p$ = 0.001). In addition, gender and age had a significant impact on asset bids (*gender*: $p$ = 0.036, *age*: $p$ = 0.022). Bids made by females were lower than those made by males, and for all subjects, the older a subject was, the higher the bid made was.

We also used the subjects' differences in bids between ordinary and socially responsible assets as the dependent variable and took risk preferences, the perceived effectiveness of charity donations, gender, age, educational level, and income level as covariates (Model 5). Doing so was equivalent to imposing a restriction on Model 4 and fixing the coefficient of *OI_bid* to 1. The results still show significant differences in the asset bids of the different stimulation groups ($F_{2,87}$ = 6.409, $p$ = 0.003, $\eta^2$ = 0.128). This result indicates that different stimulation groups show significant differences in their non-financial motivations to engage in SRI. The subjects who received anodal stimulation show significantly more non-financial motivation to engage in SRI than those who received sham ($p$ = 0.004) and cathodal stimulation ($p$ = 0.025). However, no significant differences were found between the cathodal and sham stimulation groups. In addition, the greater the perceived effectiveness of charity donation was, the higher the bid was ($p$ = 0.015). Gender (females' bids were lower than males') and age (older subjects made higher bids) also had significant impacts on asset bids (*gender*: $p$ = 0.039, *age*: $p$ = 0.044). Notably, the impact of risk preferences on bids was no longer significant ($p$ = 0.281), further verifying that the method used to calculate the difference between socially responsible asset bids and ordinary asset bids could effectively offset the influence of financial motives on SRI decision-making.

For the real SRI task, we took the subjects' bids for the real socially responsible fund as the dependent variable and took risk preferences, the perceived effectiveness of the socially responsible fund, the return and risk performance evaluations of the Xingquan Social Responsibility Mix Fund, gender, age, educational level, and income level as covariates (Model 6). We found that the impact of the stimulation mode on the fund bids to still be very significant ($F_{2,85}$ = 8.388, $p < 0.001$, $\eta^2$ = 0.164). The fund bids of the anodal stimulation group were significantly higher than those of the sham ($p$ = 0.007) and cathodal stimulation groups ($p$ = 0.001), while there were no significant differences between the cathodal and sham stimulation groups ($p$ = 1.000). This result is consistent with the results of the one-way ANOVAs. In addition, gender (females make lower bids than males) and risk preferences (the stronger risk preferences are, the higher the bid becomes) had significant impacts on the fund bids *(gender*: $p$ = 0.01, *risk preference*: $p$ = 0.001). The return and risk performance evaluations were not significant, indicating that the subjects' bids were not relying on their expectations surrounding SRI risks and returns (*fund_return*: $p$ = 0.294, *fund_risk*: $p$ = 0.219). Moreover, we still did not find a significant effect of the stimulation mode on the subjects' perceived effectiveness of socially responsible fund after controlling for gender, age, educational level, and income level ($F_{2,89}$ = 0.592, $p$ = 0.555, $\eta^2$ = 0.013).

Finally, to test whether the stimulation modes affected the risk preferences of the subjects, we used risk preferences as the dependent variable and gender, age, educational level, and income level as covariates (Model 7). Again, consistent with the results of the one-way ANOVAs, we found no significant differences in the risk preferences of the subjects under different stimulation conditions ($F_{2,89}$ = 0.674, $p$ = 0.512, $\eta^2$ = 0.015). This result shows that the stimulation modes did not affect the subjects' risk preferences.

## DISCUSSION

With the rapid development of SRI in recent years, the motivation to make SRIs has become an important topic. Studies have found that SRI is driven by both financial and non-financial motives (Lewis and Mackenzie, 2000; Statman, 2004; Nilsson, 2008). These non-financial motives are usually attributed to altruism, but other factors may also account for these motives, such as reputational concern and social conformity. This study explored whether altruism plays an important role in SRI decision-making. We used tDCS to temporarily modulate activity in the rTPJ and tested how different stimulation modes affected subjects' donation and SRI behaviors. Neuroscientific studies have found that the rTPJ plays an important role in the psychological mechanism of altruism, especially in the processing of moral-material conflicts (Morishima et al., 2012; Jeurissen et al., 2014; van der Meulen et al., 2016; Obeso et al., 2018; Li et al., 2020). Based on this evidence, we tested the following two hypotheses. First, modulating activity in the rTPJ using tDCS will alter the subjects' processing of moral-material conflicts, changing the subjects' donation behaviors. Second and more importantly, if altruism does play an important role in SRI decision-making, changes in the subjects' processing of moral-material conflicts will also lead to changes in their SRI behaviors.

We conducted four sequential tasks in an experiment. First, we tested whether modulating activity in the rTPJ successfully altered the subjects' levels of altruism through the use of a donation task. Second, we designed a simulated SRI task and compared the subjects' willingness to invest in an ordinary asset and their willingness to invest in a socially responsible asset to study whether different stimulation modes changed non-financial motives to engage in SRI. On this basis, we further studied the willingness to invest in a real socially responsible fund under different stimulation modes through the use of a real SRI task. Finally, to control for the subjects' risk preferences regarding their investment decisions, we measured this variable through the use of a risk preference measurement task. We found that enhancing activity in the rTPJ increased the subjects' donation amounts while decreasing activity in the rTPJ reduced donation amounts. This result verifies our first hypothesis and is consistent with the conclusions of existing studies (Morishima et al., 2012; Hutcherson et al., 2015; Strombach et al., 2015). More importantly, by observing bids made for the simulated and real socially responsible asset (fund) under different stimulation modes, we found that the subjects who received anodal stimulation also showed a stronger willingness to invest in SRI from non-financial motives. Therefore, our second hypothesis is also verified, and we have reason to believe that altruism does play an important role in SRI decision-making. Increasing activity in the rTPJ effectively reduced the monetary self-interest of the subjects, increasing their willingness to make SRIs.

Nevertheless, we found that a decrease in rTPJ activity did not have a significant impact on SRI behavior. Although the "anodal excitation, cathodal inhibition effect" (AeCi-effect, Jacobson et al., 2012) has been observed in many studies investigating the motor system and other cortical regions, such as the visual cortex (Antal et al., 2003; Lang et al., 2004; Furubayashi et al., 2008; Stagg et al., 2009), a meta-analysis showed that the AeCi-effect has rarely been found in cognitive studies (Jacobson et al., 2012; Brückner and Kammer, 2017). In most cases, anodal stimulation has indeed improved performance, while the effect and direction of modulation caused by cathodal tDCS may depend on the task investigated (Brückner and Kammer, 2017). In our study, cathodal stimulation inhibited the subjects' behaviors for the donation task but not for the SRI task, which indicates that there may still be some processing differences between charity donation and SRI. To gain more insight, we checked the subjects' perceived effectiveness of charity donation and socially responsible fund and found that anodal stimulation did not alter the subjects' perceived effectiveness of both, while cathodal stimulation decreased that of charity donation. Thus, anodal and cathodal stimulations may influence subjects' donation behaviors through different channels: An increase in rTPJ activity reduced monetary self-interest, while a decrease in rTPJ activity reduced perceived effectiveness. In contrast, in the context of SRI, an increase in rTPJ activity still reduced monetary self-interest, but the perceived effectiveness of socially responsible fund did not change because this may be determined through more rational thinking than that of charity donations.

Our study also draws some other interesting conclusions. For example, we found a significant impact of gender on bids for the socially responsible assets and fund, which can be compared to the evidence of previous studies (Nilsson, 2008; Cheah et al., 2011; Dorfleitner and Utz, 2014). Notably, these studies found female investors to be more willing to make SRIs than male investors, while we found males to be more willing to make SRIs than females. A possible explanation could be that females may be more cautious about new concepts or about engaging in unfamiliar practices such as SRI, which is not yet a well-known investment philosophy in China. In addition, we found that the subjects' risk preferences significantly affected their investment bids. In line with intuition, the subjects with stronger risk preferences made larger bids for their investments. We also investigated the role of perceived effectiveness in SRI. Perceived effectiveness refers to the fact that people are more likely to take actions when they believe that their actions will help solve certain problems (Straughan and Roberts, 1999). Beal et al. (2005) showed that investors gain psychological value when they feel that they have made contributions to a worthy cause or have done something for others, and this feeling serves as an important impetus for them to make SRIs. Studies have also found a significant positive correlation between perceived effectiveness and the willingness to make SRIs (Nilsson, 2008; Wins and Zwergel, 2016; Brodback et al., 2019). Consistent with the above conclusions, our study shows that the stronger subjects' perceived effectiveness was, that is, the more they believed that charity donation and SRI could have positive effects on society and the greater their willingness to make SRIs became.

Nevertheless, this work presents some limitations. First, although we balanced the gender ratio across the stimulation conditions, the number of male and female subjects was not the same due to limitations during recruitment. We also ran analyses on male and female subject samples. The results for the female subject sample (72 subjects) are the same as those for the overall sample, while the results for the male subject sample (24 subjects) show the same tendencies but are not significant. The insignificant results of the male subject sample may be due to a gender difference in the function of the TPJ in the processing mechanisms. The latter case is also supported by previous studies showing gender differences in TPJ activation in investment decision-making occurring in trust games and in other social cognitive tasks, with higher activation found in males than in females (Schulte-Rüther et al., 2008; Luo et al., 2015; Lemmers-Jansen et al., 2017, 2019). Nevertheless, the neurobiological and psychosocial factors behind such differences are still unclear and need to be explored by future studies. Second, the stimulation of the rTPJ may also affect several other brain functions. For example, Gerfo et al. (2019) found that anodal tDCS over the rTPJ increased the number of antisocial punishment choices made compared to sham conditions. Wang et al. (2019) found enhanced activity in the rTPJ via anodal stimulation to increase the accuracy of a participant's inference of the strategies of others or a participant's concern for others and thus helped a participant bid optimally in a competition context. Although the tasks used in our study did not involve punishment decisions or interactions between subjects, it is still difficult to exclude the possibility that some functions related to the decision-making process involved in the experiment may also have been modified by the stimulations. Furthermore, with the other electrode placed over the subject's left cheek, the current may also have flowed over somatosensory and left hemisphere parietal/temporal regions. The method used to place electrodes in this study was adopted from previous studies and was used to reduce the impact of the non-target electrode on the brain cortex (Berryhill and Jones, 2012; Tseng et al., 2012; Mai et al., 2016). By placing the non-target electrode on the contralateral cheek instead of on other cortex areas, we tried to reduce the inhibition of activity in other cortex areas. Nevertheless, this is a methodological limitation of our study.

Other limitations may also include the particularities of our subjects. The subjects involved in our study are university students, and these young, smart, and educated subjects may have different underlying psychological/social beliefs that might influence investment behaviors relative to the broader population. In addition, there are differences between asset or fund bids and real-world investment decisions. For instance, to be more consistent with previous studies, we did not test the effect of stimulations on the magnitude of investment, which is a crucial facet of real-world investment decisions.

To summarize, this study used tDCS to temporarily modulate activity in the rTPJ and tested how different stimulation modes affected subjects' donation and SRI behaviors. We found that anodal stimulation increased the subjects' donation amounts, while cathodal stimulation decreased their donation amounts. More importantly, we found that anodal stimulation could enhance subjects' willingness to make SRIs, suggesting that altruism plays an important role in SRI decision-making. Nevertheless, cathodal stimulation did not reduce subjects' willingness to make SRIs. Furthermore, cathodal stimulation changed subjects' perceived effectiveness of charitable donation but not that of socially responsible fund. This may help explain the inconsistent effects of cathodal stimulation on charitable donations and SRI behaviors. The main contribution of our study lies in its pioneering application of tDCS to conduct research on SRI behaviors and provision of neuroscientific evidence regarding the role of altruism in SRI decision-making. As our results show that altruism does play an important role in SRI decision-making, practical applications could involve increasing the amount of SRI with methods that can evoke or increase altruism. Our results also imply that increasing and decreasing activity in the rTPJ may lead to different processing mechanisms involved in altruistic tasks.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the Key Laboratory of Applied Brain and Cognitive Sciences, Shanghai International Studies University. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

XY, WM, SC, MG, and JZ designed the experiment, revised the manuscript, and approved the version to be published. WM, SC, and MG performed the experiment. XY, WM, and SC analyzed the data and wrote the manuscript. WM and SC created the figures. All authors contributed to the article and approved the submitted version.

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# More Negative FRN From Stopping Searches Too Late Than Too Early: An ERP Study

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It is widely known that the feedback from a decision outcome may evoke emotions like regret, which results from a comparison between the gain the decision-maker has made and the gain he/she might make. Less is known about how search behavior is linked to feedback in a sequential search task such as searching for jobs, employees, prices, investments, disinvestments, or other items. What are the neural responses once subjects decide to stop searching and receive the feedback that they stopped too early or too late compared with the optimal stopping time? In an experimental setting of a search task, we found that the feedback-related negativity (FRN) induced by the feedback from stopping too late was more negative than stopping too early, suggesting that subjects might experience stronger regret when stopping too late. Subjects preferred to stop searching earlier if the last feedback was that they stopped too late, and vice versa, although they did not always benefit more from such adjustment. This might reflect general patterns of human learning behavior, which also manifests in many other decisions. Gender differences and risk attitudes were also considered in the study.

**Keywords: search behavior, regret, ERPs, feedback, gender, risk attitude**

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## INTRODUCTION

Since people are often confronted with dynamic choice problems in their daily lives, search behavior has long been a topic of considerable interest in job searches (McCall, 1970; Burdett, 1978; Cox and Oaxaca, 1989; Le Barbanchon et al., 2021), information searches (Punj and Staelin, 1983; Brucks, 1985), and price searches to exercise an option or terminate an investment (Ihlanfeldt and Mayock, 2012; Yang et al., 2018).

Previous studies pay lots of attention to the search duration and reservation value of search behavior. Individuals preferred to stop search earlier than the optimal search duration derived from the rational risk-neutral assumption (Schunk and Winter, 2009). Viefers (2012) found that ambiguity-averse decision-makers reacted to ambiguity by postponing the investment relative to a situation where there was a risk. In search tasks, the reservation value is the least favorable point at which one will accept to stop searching. Asano et al. (2015) designed a laboratory experiment to explore the effect of ambiguity on subjects' search behavior. They observed that subjects reduced their reservation points in the face of ambiguity over point distribution. In a real-time-search laboratory experiment, subjects' reservation wages declined sharply over time. However, in the widely accepted labor market search models, the payoff-maximizing reservation wage was constant (Brown et al., 2011).

The feedback of decisions is essential since people tend to compare the actual benefit from "what is" with "what might have been." The feedback about actual and foregone outcomes might induce emotions like regret as a motivation for decisions (Humphrey, 2004). Regret comes from an inner source when the outcome of a decision is worse than the other decision. What's more, feedback has a significant effect on individual behavior in terms of the search strategy. Individuals were likely to deviate from the optimal strategy (Sonnemans, 2000), but they could learn from the search outcomes and make adjustments. For example, if they observed that shortening search durations might yield a higher payoff, they would stop searching earlier in subsequent searches to adjust this behavior (Einav, 2005).

Literature has identified an ERP component, feedback-related negativity (FRN), that may be especially relevant to feedback-driven emotion like regret (Luo et al., 2011). The FRN peaks approximately 200–300 ms following feedback, especially indicating negative compared to positive feedback. Moser and Simons (2009) suggested that the FRN reflected a context-sensitive signal that integrated information about current and past actions, thoughts, and emotions. They interpreted their results to mean that the FRN should be largest on trials in which regret is largest. FRN is more pronounced for negative feedback associated with unfavorable outcomes than for positive feedback. Search outcomes are always negative when compared with the best payoff. People seldom make optimal search decisions, and their search outcome is worse than the best outcome generated from the optimal search decision. Therefore, the FRN is suited to investigate the neural mechanism of feedback in search behavior.

Unlike the static choice problems, the feedback in search behavior compares the benefit from the chosen option with the benefit from the alternative options. It shows whether individuals stop search too late or too early compared with the optimal stopping time to earn the best payoff. The highest price in a trial would yield the best payoff. Therefore, there are two kinds of feedback in a sequential search task by comparing the stop time with the timing of the highest price. First, subjects stop searching after the appearance of the highest price (hereafter, "stop searches too late"), and second, subjects stop searching before the arrival of the highest price (hereafter, "stop searches too early"). Which scenario induces a more negative FRN? This question has not been discussed in the literature.

Based on the previous findings, there are some differences between "stop searches too late" and "stop searches too early." Sonnemans (1998) believed that subjects who stopped early had less opportunity to learn than subjects who stopped late because the difference in the amount of information gathered by the subjects caused a difference in learning opportunity. Seale and Rapoport (2000) found stopping too early was more costly than stopping too late. What's more, some psychology studies consider two forms of regret, namely action and inaction regret. Inaction was associated with greater short-term regret than action (Gilovich and Medvec, 1995; Abendroth and Diehl, 2006; McElroy and Dowd, 2007). In our experiment, the feedback of "stop searches too late" was inaction as subjects had already seen the highest price, but they did not take action to sell the stock at the timing of the highest price. The feedback of "stop searches too early" was an action. Therefore, we were interested in exploring whether subjects would have different neural responses like FRN, which probably had a close relationship with regret, when stopping searches too late and too early.

To test our hypothesis concerning the modulation of the FRN by different kinds of feedback, we designed a sequential search task composed of 50 trials including different kinds of feedback described above. The stock price was randomly drawn from a uniform distribution in each trial and presented to subjects in each of the 20 periods. Subjects were asked to decide when to sell their stocks within a trial. In this trial, once subjects stopped searching to sell their stocks at a price, feedback about the highest price was immediately presented to the subjects. Their event-related potentials (ERPs) were recorded.

In this study, there were three types of feedback when comparing the optimal stopping time at which the highest payoff yielded with subjects' own stopping time: the subjects stop searches too late, too early, or optimally. We also compared the subjects' average search duration and ERPs. Risk attitudes and gender differences were considered in our study.

# MATERIALS AND METHODS

## Subjects

Twenty-three students in Zhejiang University from different majors were recruited via an advertisement posted on BBS. There were 22 valid data for analysis (7 females, mean age = 23.00 ± 2.29). One subject's data was rejected because his data was not completely recorded due to the loose contact of the device. All of the subjects were right-handed with normal or corrected-to-normal vision. The show-up fee of the experiment was CNY20 (around 3.1 dollars). An additional monetary reward was associated with subjects' performance. In terms of the exchange rate with actual earnings, 100 tokens in the experiment equaled CNY1. Informed consent was obtained in writing before the experiment, and the subjects were paid for their participation after the experiment. The study was approved by the Ethics Committee, Neuromanagement Lab, Zhejiang University.

## Experimental Design

### The Search Task

We designed a sequential search task (**Figure 1**) to investigate how search behavior was linked to the feedback in a dynamic search task, and the difference between the degrees of the emotion of regret triggered once subjects received the feedback about whether they stopped searches too early or too late, compared with the optimal stopping time that yielded the highest payoff.

The task consisted of two blocks of 25 trials each. The subjects were endowed with a stock portfolio at a fixed cost before each trial. Each trial began with a fixation in the center of the screen. Within each trial, the subjects who acted as investors decided when to sell their stocks across 20 periods. The price of the stock portfolio was randomly drawn from a uniform distribution from 2,000 to 4,000 and was presented on the screen at the beginning of each period. All the prices had been randomly generated by the computer before the experiment and were the same for all subjects. Once the subject decided to sell his/her stocks at the current price, the search task was finished, and the

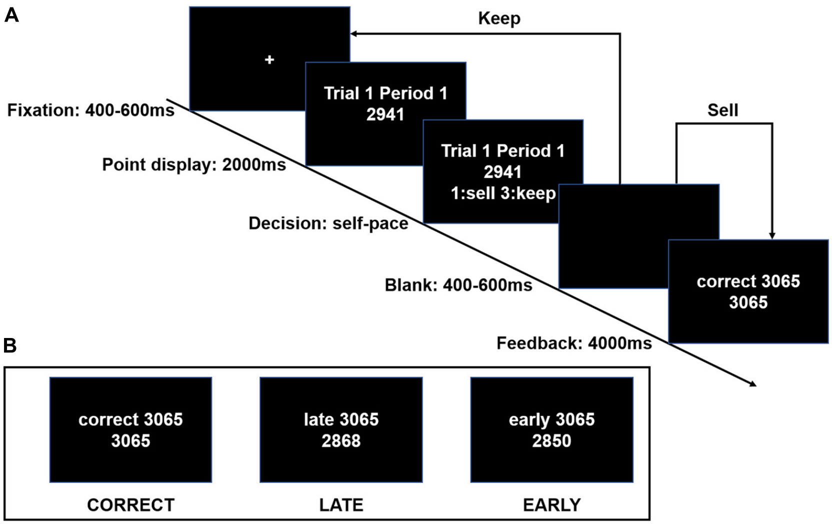


**FIGURE 1 |** Experimental design. **(A)** Single-trial settings. Each trial began with a fixation in the center of the screen. Within each trial, subjects decided when to sell their stocks in 20 periods. Once the subject decided to sell his/her stocks at the current price, the searching task was finished, and feedback was presented. If the subject rejected to stop (keep), he/she returned to the fixation of the next period. They had to sell the stocks in a limited 20 periods in each trial. **(B)** Three examples of feedback.

information about the highest price in this trial was presented. Finally, this trial was concluded, and the accepted price of the stock portfolio was converted into a payment. If the investor rejected to stop (keep), then he/she returned to the fixation of the next period. The subject had to sell the stocks in a limited 20 periods in each trial.

As **Figure 1** shows, three examples of outcome feedback presentation in the final block. Comparing the optimal stopping time that yielded the highest payoff with subjects' own stopping time, subjects were, respectively informed of "correct," "late," and "early." In a particular trial, for example, if subjects sold their stocks at period 12 while the highest price had appeared at period 9 or was not presented until period 15, then they were informed of their having stopped "late" or "early," respectively, by the presented feedback in the final block. In the first line, the number 3065 represents the highest price of the stock portfolio in Trial 1, while the number in the second line represents the subjects' accepted price.

Feedback was given once subjects stop searching in one trial. There were three types of feedback comparing the optimal stopping time, yielding the highest payoff, with the subjects' own stopping time, that is, "CORRECT," "LATE," and "EARLY." CORRECT indicated that subjects sold their stock at the highest price; LATE indicated that they sold their stock after the highest price appeared (the subjects stopped searches too late); EARLY indicated that they sold their stock before the time the highest price appeared (the subjects stopped searches too early).

The subjects used a numpad to choose to sell or keep the portfolio of stocks. Pressing number 1 meant "sell" while pressing number 3 meant "keep." The search task was repeated across 50 trials. Only one trial was randomly selected to determine the real payoff for the subjects.

### Procedure

The experiment was conducted with the software E-Prime. Before the experiment, all of the subjects were asked to wash and blow-dry their hair. They then seated themselves comfortably on a chair that was one meter away from a 17-inch CRT screen in an acoustically isolated and electrically shielded room. After a public reading of the instructions, two trials were conducted to facilitate subjects to practice the search task. Then, the first block of the search task was started. The trials were conducted one at a time. After the first block of the search task, the subjects were reminded to sit comfortably and rest for 5 min. When the rest time was finished, the second block of the search task was started. At the end of the search task, we used a lottery choice task (Holt and Laury, 2002) shown in **Table 1** that was modified from previous studies to measure the risk attitude of the subjects, which consisted of 10 paired lottery choices between a safe option and a risky option. Each subject's degree of risk aversion was measured by the number of safe options chosen by him/her.

## ERP Recordings

We used a 64-channel ERP system (Scan 4.3, Neurosoft Labs, Inc.) to record EEG with electrodes mounted according to the extended international 10/20 system during the experiment. The raw EEG and EOG data were low-pass filtered with a cut-off frequency at 30 Hz (24 dB/Octave), and then re-referenced to the average of the left and right mastoids. Eye blinks and movements were recorded from left supraorbital and infraorbital electrodes, while the horizontal EEG was recorded from electrodes placed 1.5 cm laterally to the left and right external canthi. All electrode impedance was maintained below 5 kΩ. The raw EEG data were visually inspected for artifacts in an off-line analysis first. Eye movement artifacts were corrected with an ocular artifact correction algorithm provided by Neuroscan 4.3 software. Next,

**TABLE 1** | The 10-paired lottery choice task by Holt and Laury (2002).

| No. | Option A | Option B | Expected payoff difference |
|---|---|---|---|
| 1 | 1/10 of CNY 2.00, 9/10 of CNY 1.60 | 1/10 of CNY 3.85, 9/10 of CNY 0.10 | CNY 1.17 |
| 2 | 2/10 of CNY 2.00, 8/10 of CNY 1.60 | 2/10 of CNY 3.85, 8/10 of CNY 0.10 | CNY 0.83 |
| 3 | 3/10 of CNY 2.00, 7/10 of CNY 1.60 | 3/10 of CNY 3.85, 7/10 of CNY 0.10 | CNY 0.50 |
| 4 | 4/10 of CNY 2.00, 6/10 of CNY 1.60 | 4/10 of CNY 3.85, 6/10 of CNY 0.10 | CNY 0.16 |
| 5 | 5/10 of CNY 2.00, 5/10 of CNY 1.60 | 5/10 of CNY 3.85, 5/10 of CNY 0.10 | –CNY 0.18 |
| 6 | 6/10 of CNY 2.00, 4/10 of CNY 1.60 | 6/10 of CNY 3.85, 4/10 of CNY 0.10 | –CNY 0.51 |
| 7 | 7/10 of CNY 2.00, 3/10 of CNY 1.60 | 7/10 of CNY 3.85, 3/10 of CNY 0.10 | –CNY 0.85 |
| 8 | 8/10 of CNY 2.00, 2/10 of CNY 1.60 | 8/10 of CNY 3.85, 2/10 of CNY 0.10 | –CNY 1.18 |
| 9 | 9/10 of CNY 2.00, 1/10 of CNY 1.60 | 9/10 of CNY 3.85, 1/10 of CNY 0.10 | –CNY 1.52 |
| 10 | 10/10 of CNY 2.00, 0/10 of CNY 1.60 | 10/10 of CNY 3.85, 0/10 of CNY 0.10 | –CNY 1.85 |

the EEG data was segmented from −200 to 800 ms relative to the target onset. All of the trials in which EEG voltages exceeded a threshold of ±80 μV during the recording epoch were excluded from averaging. The EEG recordings for every subject were separated into two kinds of feedback, LATE feedback and EARLY feedback.

## Data Analysis

The Mann–Whitney statistical method was a non-parametric test and was always adopted to analyze the behavioral data. We compared the different average search duration in this trial after the reveal of the LATE and EARLY feedback. We also examined the effect of gender and risk attitude on the search behavior of subjects. Random-effects generalized least squares regression was used to further explore the concrete degree of the feedback type's effect on search duration.

Repeated measures analysis of variance (ANOVA) was adopted to perform a statistical analysis of ERP results. In this study, the dependent variable of ANOVA was the amplitudes of FRN, and the independent variables were feedback with two types (LATE vs. EARLY feedback) and electrodes with six levels (F3, Fz, F4, FC3, FCz, FC4). As **Figure 2** shown, we focus on these six electrodes on which the FRN was great (Leng and Zhou, 2010; Zheng et al., 2017; Yaple et al., 2018).

# RESULTS

## Behavioral Results

From the average perspective, subjects' search behavior was affected by the different feedback types of searches, gender, and risk attitude. Our analysis focused on the LATE and EARLY trials rather than the CORRECT trials because almost no subject could perfectly stop searches "correctly." The direct comparison showed different search durations in this trial after revealing different feedback in the last trial (**Figure 3A**). The average search duration across all of the trials after the LATE feedback was significantly shorter than after the EARLY feedback (mean ± SD, 9.12 ± 2.10 vs. 10.46 ± 1.99, Mann–Whitney test, $p$ = 0.000). We also found that female subjects tended to stop later than male subjects (10.61 ± 5.05 vs. 9.67 ± 5.29, Mann-Whitney test, $p$ = 0.0046; **Figure 3B**), which was in line with the previous study (Ibanez et al., 2009). Further analysis also indicated that the risk-averse subjects stopped earlier than the non-averse subjects, including risk-seeking and risk-neutral subjects (9.70 ± 5.05 vs. 10.71 ± 5.64, Mann–Whitney test, $p$ = 0.0093; **Figure 3C**).

We also used random-effects generalized least squares regression to further examine the effect of feedback type on subjects' search duration and the effect of gender and risk attitude. The regression results are displayed in **Table 2**. The coefficients of LATE and RiskAverse are significantly negative and the coefficients of Female are significantly positive in column (1) without control variables and in column (2) with control variables. In line with the result of the Mann–Whitney test, taking the regression result in column (2) for example, the duration under LATE feedback is significantly 0.74 shorter than the duration under EARLY feedback. Furthermore, female subjects' search duration is 1.37 longer than male subjects' search duration and risk-averse subjects' search duration is 1.14 shorter than not risk-averse subjects' search duration. The regression in column (3) of **Table 2** is to test whether gender and risk attitude

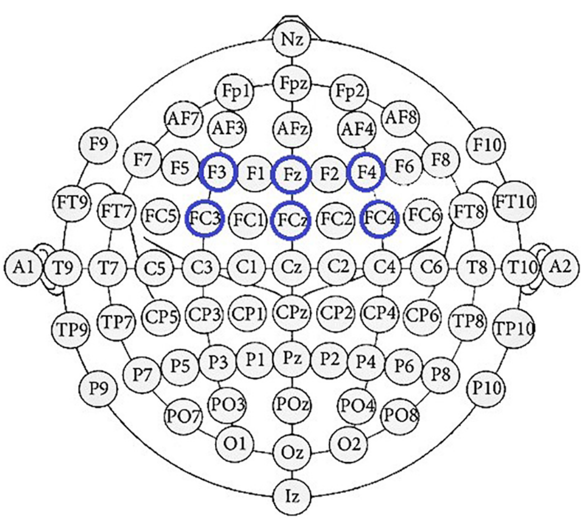


**FIGURE 2** | The extended 10–20 International system of EEG electrode placement. Blue circles represent the channels of feedback-related negativity (FRN).

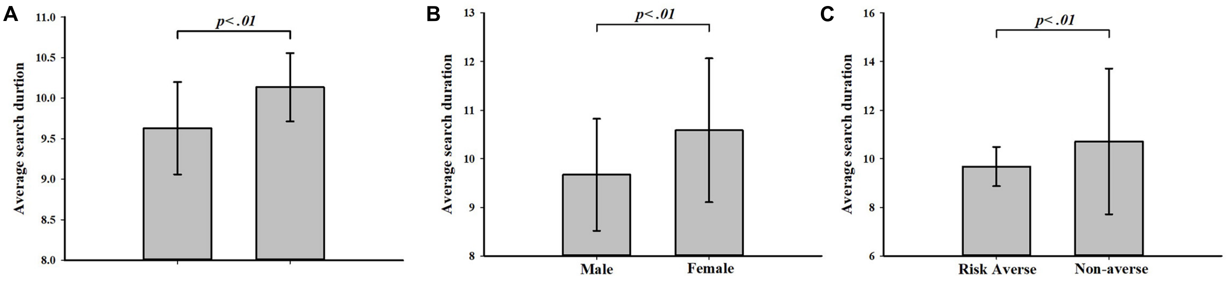


**FIGURE 3 |** Average search duration (+5% standard error) under different conditions. **(A)** Average search duration under two types of feedback. **(B)** Average search duration of male and female subjects. **(C)** Average search duration of risk-averse subjects and non-averse (risk-seeking and risk-neutral) subjects. Risk aversion increases with the number of choosing safe options out of the 10 paired choices. The subjects were clarified as risk-averse if the number of safe options was more than 4 and non-averse if the number of safe options was equal to or less than 4.

moderate the effect of feedback type on search duration through the interaction of feedback type and gender/risk attitude. The coefficient of LATE becomes not significant since more variables are added to the regression. The coefficients of the interaction terms are not significant, which shows that the moderating effect of gender and attitude doesn't exist.

## ERP Results

For the FRN analysis, we measured the average amplitude in the 200–300 ms time window after feedback onset (Falkenstein et al., 2000; Gehring and Willoughby, 2002). **Figure 4** shows the grand average wave elicited by LATE and EARLY feedback at the F3, Fz, F4, FC3, FCz, and FC4. Here, a 2 (feedback type: LATE, EARLY) × 6 (Electrodes: F3, Fz, F4, FC3, FCz, FC4) repeated measures ANOVA on FRN amplitudes depicted the significant main effect of feedback type [$F(1,21) = 16.747$, $p = 0.001$, $\eta_p^2 = 0.444$]. The amplitude of FRN triggered by the LATE feedback (mean ± SD, 5.71 ± 0.74) was significantly more negative than that under the EARLY feedback (mean ± SD, 8.05 ± 0.99). Therefore, we supposed that the more negative amplitude of FRN might indicate a stronger experience of regret (Moser and Simons, 2009; Luo et al., 2011; Qi et al., 2011).

To test the gender differences in the amplitude of FRN, we employed a repeated measures ANOVA with feedback type (LATE, EARLY), Electrodes (F3, Fz, F4, FC3, FCz, FC4), and gender (male, female) in which gender is a within-subject factor. The main effect of feedback was still significant, $F(1, 20) = 18.01$, $p < 0.001$, $\eta_p^2 = 0.474$. Importantly, there was also a significant main effect of gender, $F(1, 20) = 5.99$, $p = 0.024$, $\eta_p^2 = 0.230$. Male subjects had a more negative FRN response to both LATE feedback and EARLY feedback than female subjects, as **Figure 5A** shows. However, the interaction between feedback and gender did not reach significance ($p > 0.1$, $\eta_p^2 = 0.059$).

Risk-averse subjects and non-averse subjects displayed considerably different patterns in the waves of FRN (**Figures 5B,C**, repeated measures ANOVA with feedback type (LATE, EARLY) and Electrodes (F3, Fz, F4, FC3, FCz, FC4), $F(1,15) = 20.607$, $p < 0.001$, $\eta_p^2 = 0.579$, for risk-averse subjects; $F(1, 5) = 0.701$, $p > 0.1$, $\eta_p^2 = 0.123$, for non-averse subjects). The repeated measures ANOVA on FRN amplitudes revealed a significant main effect of feedback type only among risk-averse subjects.

**TABLE 2 |** The regression results.

| | Dependent variable: Search duration | | |
|---|---|---|---|
| **Independent variables** | **(1)** | **(2)** | **(3)** |
| LATE | −0.66* (0.36) | −0.74* (0.39) | −0.21 (0.71) |
| Female | 1.31*** (0.39) | 1.37*** (0.39) | 1.55*** (0.50) |
| RiskAverse | −1.11*** (0.40) | −1.14*** (0.39) | −0.95* (0.51) |
| LATE × Female | | | −0.51 (0.78) |
| LATE × RiskAverse | | | −0.50 (0.81) |
| Constant | 10.60*** (0.37) | 9.30*** (1.85) | 9.24*** (1.85) |
| Control variables | No | Yes | Yes |
| R square | 0.0932 | 0.1123 | 0.1248 |
| Observations | 933 | 933 | 933 |

****1% significance level.*
**10% significance level.*
*Standard error is in the parentheses.*
*Dependent variable: Each subject's search duration in every trial.*
*Independent variable:*
*LATE: = 1 if last trial's feedback is "LATE"; = 0 if last trial's feedback is "EARLY."*
*RiskAverse: = 1 if subjects choose more than four Option A in the lottery choice task.*
*LATE × Female: Interaction of variable LATE and Female.*
*LATE × RiskAverse: Interaction of variable LATE and RiskAverse.*
*Control variables: Age and OptimalDeviation are control variables.*
*OptimalDeviation is defined as the difference between the price yielding highest payoff and the price that subjects sell at in the last trial.*
*"Yes" means these control variables are included in the regression, and "No" means these control variables are not included in the regression.*

## Feedback-Driven Adjustment

Post-decision regret, elicited by the reveal of feedback indicating more profit from an alternative decision, is the driver of learning (Ert and Erev, 2007; Marchiori and Warglien, 2008). In general, a decision-maker adopts a feedback-driven adjustment (Einav, 2005). Thus, in our experimental setting, we assumed that subjects would shorten their search duration in this trial after receiving the LATE feedback and increase their search duration after receiving the EARLY feedback.

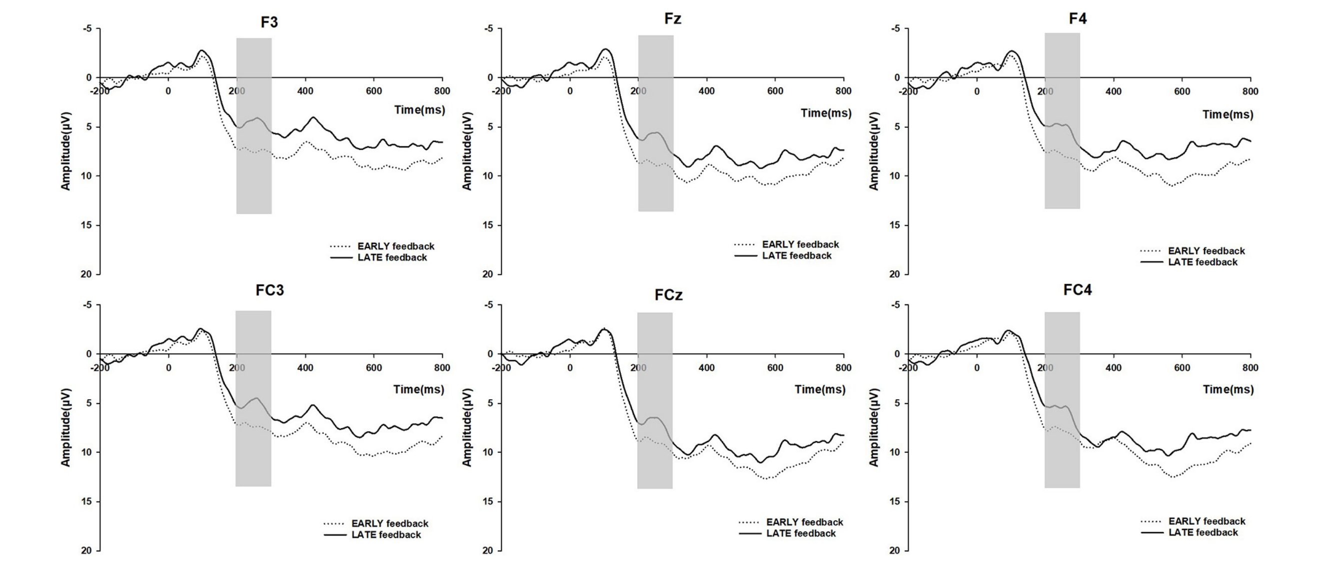


**FIGURE 4 |** Grand average ERP waves for EARLY feedback/LATE feedback trials at the F3, Fz, F4, FC3, FCz, and FC4.

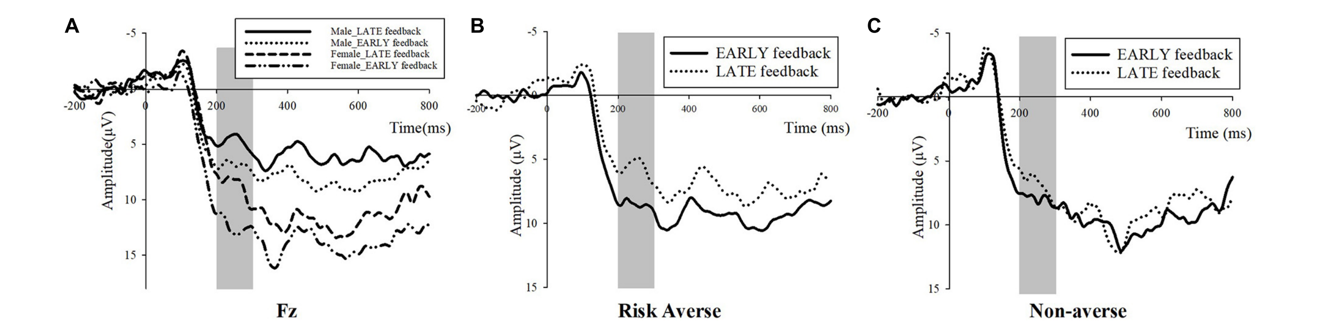


**FIGURE 5 | (A)** Gender difference in FRN amplitude (7 females, 15 males). **(B)** FRN amplitude under two types of feedback among risk-averse subjects (16 risk-averse subjects, 6 risk-neutral and risk-seeking subjects). **(C)** FRN amplitude under two kinds of feedback among non-averse (risk-seeking and risk-neutral) subjects.

Most of the subjects (68.98% overall trials) were observed to adjust their search duration in this trial according to the feedback from the last trial. Obviously, the subjects preferred to learn from failures and adopt feedback-driven adjustments in their search decisions. However, **Figure 6** illustrates that there is no difference between the profit made from trials in which subjects adjusted search duration according to feedback and trials in which subjects did not do so (Mann-Whitney test, $p = 0.339$). Subjects tended to adjust their decisions in the search task, even though they were uncertain whether or not the profit made by adjusting would be higher.

## DISCUSSION

The present study aimed to determine whether the LATE feedback (stop searching too late) or EARLY feedback (stop searching too early) induced a more negative FRN which probably reflected stronger feelings of regret. ERP data demonstrated that compared with the optimal stopping time yielding the highest payoff, people had a more negative FRN when stopping searching too late than too early. One possible explanation for the difference in FRN amplitude between the LATE feedback and EARLY feedback was that people might feel much more regret when they found that they had stopped searching too late than too early. Moreover, such a type of regret could drive people to adjust their search behavior. Specifically, in this trial, subjects stopped searching earlier after receiving the LATE feedback and stopped searching later after receiving the EARLY feedback.

Understanding the neural basis of choice in optimal stopping problems is of fundamental importance because it relates to many problems of economic decision-making (Houser et al., 2004; Viefers, 2012). Our paper is the first to investigate the neural response to feedback in a dynamic search framework to the best of our knowledge. The difference between FRN amplitude under two types of feedback suggested that subjects might experience different

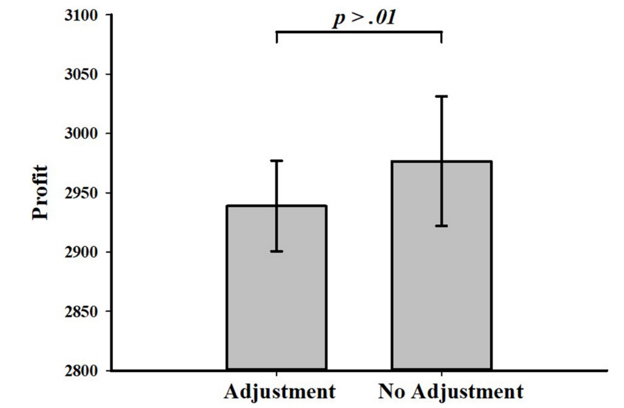


**FIGURE 6 |** Profit made by using and not using feedback-driven adjustment.

degrees of regret when they stopped their searches too late and too early.

Regret plays a vital role in decision-making (Connolly and Zeelenberg, 2002; Humphrey, 2004). Subjects were inclined to make regret-minimizing choices rather than risk-minimizing choices (Zeelenberg et al., 1996). It was reasonable that increased regret aversion might lead to more careful decisions (Reb, 2008). In our study, the emotion of regret may arise once subjects decide to stop searching and receive the feedback that they stopped too early or too late compared with the optimal stopping time. In the search task, the decision is irreversible, and there is only one opportunity to decide at a certain time. The future payoff of a decision is also uncertain. The characteristics of such decisions can evoke the experience of regret after a reveal of outcomes by which people benefit less from "what is" compared with "what might have been" (Bell, 1982; Sugden, 1985; Roese and Olson, 2014). Regret theory assumed that the utility of a chosen option additionally depended on the feelings evoked by the outcome of the rejected option (Loomes and Sugden, 1982). Individuals might experience regret because they may reflect on how much better their position would have been if they had chosen differently. This reflection may reduce the psychological experience of pleasure driven from the outcome they had chosen. However, few studies focus on emotion triggered from the revelation of the search results that may affect the subsequent search behavior.

We found that the possible neural signal of regret, the FRN amplitude, was more negative under LATE feedback than that under EARLY feedback, perhaps because subjects felt more regret over selling stocks too late rather than too early. One possible explanation relates to uncertainty; with the increase of uncertainty, the value of investment decreases (Nishimura and Ozaki, 2007). Because uncertainty is resolved when stopping a search, when the subjects were informed that they stopped earlier than the optimal stopping time, their experience of regret was compensated by the elimination of future uncertainty.

Learning driven by regret-based feedback may predict individual behavior (Ert and Erev, 2007; Marchiori and Warglien, 2008). Our results showed that regret might be triggered by the comparison between the possible highest payoff and their payoff in the sequential search task had a significant effect on the search behavior of subjects. Apparently, subjects usually adjusted their search strategy in this trial just after receiving feedback from the last trial. This might reflect general human behavior, and it is similar to what is witnessed in economic settings (Einav, 2005), organizational operations (Chuang and Baum, 2003), and surgery units within medical facilities (Kc et al., 2013). However, in our experiment, such simple learning might not have always brought more profit because, in complex financial markets, stock prices could follow random paths and were difficult to predict.

In sum, our study used ERP and a sequential search task to reveal different neural responses, the FRN, after receiving different types of feedback. These findings suggest that subjects may experience stronger regret when they stopped searching too late. Although subjects did not always benefit from adjustments, they tried to act in the opposite direction of the feedback and expected to stop their search task at a better time that was closer to the optimal stopping time. This might reflect human learning behavior, and it helps us to better understand individual search behavior, which also exists in many other aspects of human life. There are two limitations of this study. First, we did not measure subjects' feelings of regret by an emotion rating scale. Second, regret is a complex emotion related to many ERPs, but our paper focused on the FRN. In future studies, we will add the emotion rating scale to the experiment and explore the component processes underlying regret, such as P3, Pe and so on.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The Neuromanagement Laboratory Ethics Committee at Zhejiang University. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

XY, MG, LZ, and QM designed the experiment, wrote and revised the manuscript, and finally approved the version to be published. MG and LZ performed the experiment. XY and MG analyzed the data. LZ and QM drew the figures. All authors contributed to the article and approved the submitted version.

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# Influence Factors for Decision-Making Performance of Suicide Attempters and Suicide Ideators: The Roles of Somatic Markers and Explicit Knowledge

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Impaired decision-making has been observed in suicide attempters during the Iowa Gambling Task (IGT). Decision-making performance is influenced by somatic markers and explicit knowledge, but it is still unclear of the influencing role on decision-making performance in suicidal individuals. We aimed to investigate whether there is a decision-making deficit in suicide attempters, suicide ideators, as well as the distinct roles of somatic markers and explicit knowledge wherein. Thirteen suicide attempters, 23 suicide ideators, and 19 healthy controls performed the IGT. Both somatic markers (by the skin conductance responses, SCRs) and explicit knowledge (by the subjective experience rating and a list of questions) were recorded. No significant differences were found among the three groups on IGT performance, explicit knowledge, and anticipatory SCRs. IGT Performance of suicide attempters was positively correlated with explicit knowledge index while behavior performance was positively associated with the SCRs in healthy controls. These results indicate that the suicide attempters seem to apply a compensatory strategy by mostly utilizing explicit knowledge to perform normally as healthy controls in the IGT.

**Keywords: decision-making, suicide attempter, suicide ideator, somatic marker, explicit knowledge**

## INTRODUCTION

Suicide is a serious public health issue. It is the second leading cause of death among 15–29-year-olds (World Health Organization, 2017). According to the stress-diathesis model of suicidal behavior, suicide is regarded as the result of an interaction between environmental stressors and trait-like diatheses or susceptibilities to suicidal behavior, independent of psychiatric disorders (Mann et al., 1999; van Heeringen and Mann, 2014; Mann and Rizk, 2020). In recent years, many researchers have focused on the underlying neuropsychological and neurobiological mechanisms of suicide to better understand the behavior and predict who is at risk and who is not (Desmyter et al., 2011; Falcone et al., 2018). In addition, a large number of studies have revealed neurocognitive deficits in suicide attempters (Jollant et al., 2011; Richard-Devantoy et al., 2013; Giner et al., 2016).

As suicide may be considered as an outcome of an altered decision, decision making deficit may be a causal cognitive factor in suicidal behaviours (Dombrovski et al., 2010).

Jollant et al. (2005) first used the Iowa Gambling Task (IGT) to explore the performance of decision-making in affective suicidal patients and found that violent suicide attempters performed significantly worse than affective control subjects indicating the possible relationship between impaired decision-making and suicide. In a large comorbid psychiatric population, it has been found that the history of suicide attempts was significantly and independently associated with impaired decision-making (Jollant et al., 2007). Moreover, it seems to be reliable and stable that the decision-making impairment is associated with the vulnerability to suicidal behavior because it has been replicated in adolescents (Bridge et al., 2012; Ackerman et al., 2015), old-aged (Clark et al., 2011), wide-range aged (from youth to old age) suicide attempters with affective diagnosis (Jollant et al., 2005, 2007, 2010), and in those from non-clinical samples (Chamberlain et al., 2013). The meta-analysis notably confirmed a significant association between disadvantageous decision-making and suicidal behavior especially with violent means revealed that decision-making deficit may be an important factor of suicide vulnerability (Richard-Devantoy et al., 2014; Perrain et al., 2021). However, the number of studies to explore the decision-making performance of suicide ideators was rare, and the results were inconsistent (Westheide et al., 2008; Sheftall et al., 2015).

Many studies have explored the influencing factors of decision-making performance. The somatic marker hypothesis proposes that emotions play an important role in decision-making and emotion-related signals (somatic markers) measured by the skin conductance responses (SCRs), which are necessary to guide choices in an advantageous direction, especially under conditions of uncertainty (Bechara et al., 1997; Bechara and Damasio, 2005). Anticipatory SCRs for bad decks were higher compared to good decks during the IGT (Wagar and Dixon, 2006). In the article, Bechara et al. (1997) reported that overt reasoning on declarative knowledge was required for advantageous decisions, and normal subjects had consciously available knowledge to guide their decision-making. Verbal reports also reflect explicit knowledge that would instruct their decision-making performance when people behave advantageously (Maia and McClelland, 2004). Some researchers even found that only explicit knowledge was sufficient to guide IGT behaviors before differential somatic activity, and the somatic markers were not critical to succeed in the IGT (Gutbrod et al., 2006; Fernie and Tunney, 2013). The level of explicit knowledge gradually improved through the IGT, and both explicit knowledge and somatic markers are shown to be involved in decision-making in healthy subjects, which implicated that advantageous decision-making seems to be associated with two systems, namely, implicit and explicit systems (Guillaume et al., 2009). It has been found that suicide attempters exhibited the decision-making impairment with a disconnection between what they "know" and what they "do", i.e., suicidal people could not make the correct choices even if they had some level of explicit knowledge (Jollant et al., 2013). Besides, it has been found that the decision-making impairment of suicide attempters was correlated with affective lability measured as the trait, which may provide some piece of evidence for the somatic marker hypothesis in suicidal context (Jollant et al., 2005, 2010). To date, no studies have investigated the influence of both implicit and explicit systems on decision-making performance in suicide.

In the current study, we aimed to examine whether there was a decision-making deficit in non-clinical college students with suicidal thoughts or suicide attempts. We assessed both somatic markers (by the SCRs) and explicit knowledge (by the subjective experience rating and a list of questions) to explore the roles of implicit and explicit systems in the decision-making performance of suicide. Suicide attempters were hypothesized to perform worse than healthy controls and suicide ideators in a decision-making task and both explicit (explicit knowledge) and implicit systems (somatic markers) contributed to the decision-making deficit of suicide attempters (Hypothesis 1). Furthermore, no significant difference in decision-making performance was found between suicide ideators and healthy controls (Hypothesis 2).

## MATERIALS AND METHODS

### Subjects and Experimental Design

Participants comprised college students aged 16–24 years, recruited from a university in Tianjin, China, as a part of a large questionnaire study exploring the influencing factors of suicide. According to the characteristics of suicide, they were divided into suicide attempt (SA) group ($n = 13$), suicide ideation (SI) group ($n = 23$), and healthy control (HC) group ($n = 19$). According to the Colombia Suicide Assessment Classification (C-CASA) and the Colombia Suicide Severity Rating Scale (C-SSRS) (Posner et al., 2007, 2011), *suicide ideation* was defined as passive thoughts about wanting to be dead or active thoughts about killing oneself, not accompanied by preparatory behavior. A *suicide attempt* was defined as potentially self-injurious behavior, associated with at least some intent to die, as a result of the act, including an interrupted attempt and aborted suicide (Posner et al., 2007). All participants were interviewed by an experienced psychiatrist with the Mini International Neuropsychiatric Inventory (MINI 5.00) to confirm the psychiatric diagnosis and suicidal history. The control subjects had no personal suicidal history and any psychiatric diagnosis. This study was approved by the ethical committee of Tianjin University, and all participants signed informed consent before the experiments.

### Assessments

#### The IGT

We tested decision-making performance using the computerized version of IGT (Overman and Pierce, 2013). It consists of four decks of cards, each labeled as decks A, B, C, and D (Bechara et al., 1994, 1999). Turning any card from deck A or deck B yields 100, and turning any card from deck C or deck D yields 50. However, some cards also carry penalties, generating a large loss of 1,250 for every 10 cards of decks A and B and a small loss of 250 for every 10 cards for decks C and D. Therefore, decks A and B are risky (bad) cards with large immediate gains but long-term losses. In contrast, decks C and D are safe (good) cards with small immediate gains, but a net gain in the long run.

Participants were with a loan of 2,000 facsimile renminbi (RMB) at the beginning and were asked to win as much money as possible. They are not told how many card selections must be made (the task is stopped after a series of 200 card selections). The net score of each subject is calculated as the difference between the number of safe and risky choices, i.e., net score = (C + D) – (A + B), for the 200 choices (total score). The scores of five blocks consisting of 40 choices are also calculated for each subject, indicating changes in the pattern of choices during the game. Positive net and block scores indicate advantageous decision-making.

Instructions on the screen during the choice period were "please consider which cards to choose", and the time was fixed to 5,000 ms. After the end of the time, the guide was "please choose", so the subjects can choose one card by clicking the mouse. Outcomes were given as "you win $X" or "you lose $Y".

### Experimental Instrument

The skin electric response was measured by the MP150WS system (BIOPAC System, Inc.) at a rate of 1,000 samples per second. With two computers, one is equipped with E-Prime software to control and present experimental materials, and the other is equipped with Acqknowledge 4.3 (HongKong HTR Co., Limited, China) to record and collect data. Different keystrokes will be marked with different markers. During the whole experiment, two computers realized data communication through COM port (HongKong HTR Co., Limited).

### SCRs Recording

Electrodes were attached to the distal phalange of the first and second digits of the non-dominant hand. SCRs were recorded continuously throughout the task. Anticipatory SCRs were defined as SCRs generated during the period of the 5,000 ms interval of the selection of a deck. We analyzed the median maximal anticipatory amplitudes before the advantageous or disadvantageous choices using Matlab R2011b software. We introduced a variable, named autonomic response, defined as the median maximal anticipatory SCRs for the disadvantageous decks (A and B) minus the median maximal anticipatory SCRs scores for the advantageous decks (C and D), i.e., the difference between anticipatory SCRs before advantageous and disadvantageous choices (Guillaume et al., 2009).

### Assessment of Explicit Knowledge

The explicit knowledge was assessed by the subjective experience rating and general conscious knowledge. After every block of 40 card selection, the participants were asked to provide subjective ratings about each deck of cards, in terms of how "good" or "bad" they felt each deck was on a 1–9 Likert-type scale. The specific instructions were "So far, according to your choice, I would like you to give each deck of cards a score, based on how good or bad you feel they are. That is, one indicates that you think the deck is very poor, and nine indicates that you think the deck is very good". The questions and choices were presented on screen, and participants typed their responses to each of the questions. In addition, the subjective experience scores were analyzed by subtracting ratings of bad decks from ratings of good decks (Bowman et al., 2005).

At the end of the game, each participant was asked a list of questions. The questions were (1) tell me all you know about this game; (2) did you find any difference between the decks?; (3) suppose you select 10 new cards from the deck A/B/C/D, will you on average win or lose money? (The question is repeated for each deck.); and (4) retrospectively, if you have to choose only one deck, which one will you choose to earn as much money as possible? (Maia and McClelland, 2004; Guillaume et al., 2009). According to the answers, we assessed the level of general conscious knowledge of subjects, which was carried out as described by Maia and McClelland (2004). There are three levels of conscious knowledge: (1) level 0: the participants do not have any conscious knowledge specifying a preference for one of the two best decks; (2) level 1: the participant has conscious knowledge specifying a preference for one of the two best decks but does not have conscious knowledge about the outcomes of the decks that could provide a basis for that preference; and (3) level 2: the participant has conscious knowledge specifying a preference for one of the two best decks and has conscious knowledge about the outcomes of the decks that could provide a basis for that preference.

### Psychometric Measures

We used the Beck Scale for Suicide Ideation-Chinese Version (BSI-CV) to the assessment of suicidal ideation (Li et al., 2010b). The Beck Depression Inventory (BDI) and State Anxiety Inventory (S-AI) were used to evaluate the levels of depression and anxiety (Wang, 1999). Personality traits were assessed by the Difficulties in Emotion Regulation Scale (DERS) and Trait Anxiety Inventory (T-AI) (Wang et al., 2007).

## Statistical Analysis

Statistical analyses were conducted with SPSS 20.0 (IBM SPSS Statistics). The characteristics of the sample were described using mean and SD for quantitative variables and proportions for categorical variables. The general conscious knowledge and gender distribution differences were compared by using Chi-square tests. The ANOVA was conducted to test for group differences in IGT net scores, subjective experience, anticipatory SCRs, psychological variables, and other demographic continuous variables. The Bonferroni *post-hoc* comparison test was used when significant the main effects were present. Pearson's correlation coefficients were calculated to test for the associations between clinical variables and IGT performance. All statistical tests were two-tailed, and $p < 0.05$ were considered statistically significant.

# RESULTS

## General Variables

Clinical, demographic, and personality characteristics of subjects are shown in **Table 1**. No differences were found

**TABLE 1 |** Demographic variables, clinical variables, personality variables, and MINI diagnosis among three groups.

| | SA group ($n$ = 13) | | SI group ($n$ = 23) | | HC group ($n$ = 19) | | $F$ | $p$ |
|---|---|---|---|---|---|---|---|---|
| | $M$ | $SD$ | $M$ | $SD$ | $M$ | $SD$ | | |
| Age (years) | 18.84 | 1.14 | 20.13 | 2.20 | 20.84 | 2.01 | 4.12 | 0.02* |
| Depression | 9.92 | 8.63 | 8.91 | 7.29 | 5.37 | 4.73 | 2.07 | 0.13 |
| Suicide ideation | 16.08 | 7.11 | 11.84 | 9.38 | 4.28 | 1.90 | 11.73 | 0.00** |
| State anxiety | 36.69 | 7.31 | 35.65 | 7.32 | 35.79 | 8.00 | 0.09 | 0.92 |
| Trait anxiety | 42.92 | 6.36 | 43.87 | 9.08 | 42.74 | 6.82 | 0.13 | 0.88 |
| **Dysregulation:** | | | | | | | | |
| Emotional perception | 12.69 | 3.53 | 13.48 | 4.29 | 15.79 | 3.84 | 2.82 | 0.07 |
| Emotional acceptance | 11.77 | 4.04 | 11.77 | 5.27 | 12.32 | 4.00 | 0.08 | 0.92 |
| Emotional understanding | 10.92 | 2.66 | 10.13 | 4.10 | 10.12 | 1.91 | 0.32 | 0.73 |
| Target behavior | 14.00 | 5.49 | 14.74 | 4.85 | 12.42 | 3.59 | 1.33 | 0.27 |
| Impulse control | 11.77 | 4.27 | 12.43 | 5.71 | 10.47 | 2.80 | 0.98 | 0.38 |
| Strategy use | 16.64 | 6.35 | 18.57 | 7.92 | 16.74 | 4.19 | 0.56 | 0.58 |
| | $n$ | % | $N$ | % | $n$ | % | $\chi^2$ | $P$ |
| Sex (male) | 6 | 46.15 | 16 | 69.57 | 9 | 47.37 | 2.81 | 0.25 |
| **MINI diagnosis** | | | | | | | | |
| Major depressive episode | 1 | 7.69 | - | - | - | - | | |
| Social phobia | 3 | 23.08 | - | - | - | - | | |
| Generalized anxiety disorder | 1 | 7.69 | - | - | - | - | | |

**$p < 0.01$.
*$p < 0.05$.

**TABLE 2 |** Overall performance of different groups of subjects on the IGT.

| | $n$ | $M$ | $SD$ | $F$ | $p$ |
|---|---|---|---|---|---|
| SA group | 13 | 26.08 | 56.36 | 0.02 | 0.98 |
| SI group | 23 | 30.00 | 69.73 | | |
| HC group | 19 | 29.57 | 61.03 | | |

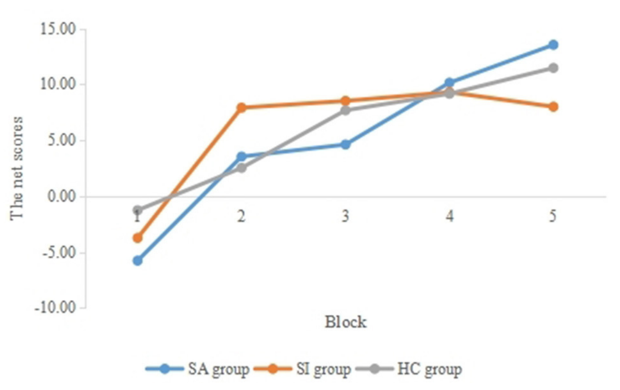


**FIGURE 1 |** Average of net scores in five blocks of different groups.

between groups in terms of gender, depression, state anxiety, and personality traits. There were significant differences in age between SA and HC groups ($p$ < 0.05). SA and SI groups had significantly higher scores of suicide ideation compared with the HC group ($p$ < 0.01; $p$ < 0.05), with no difference between the two suicidal groups ($p$ > 0.05).

## IGT Performance

There was no significant difference among the three groups on the total net score in the IGT ($p$ > 0.05), and the result was unchanged after controlling the age ($p$ > 0.05; **Table 2**).

We used 3 (group) × 5 (block) repeated measures ANOVA to explore the difference in decision-making performance in three groups over time. The results showed that the main effect of the block was significant ($F$ = 9.75, $p$ < 0.01, $\eta_p^2$ = 0.16), with a continuous increase in IGT net scores from block 1 to block 5 (see **Figure 1**). The interaction effect between group and block was not significant ($p$ > 0.05), and the main effect of the group was not significant ($p$ > 0.05). After controlling the age as the covariate, the main effect of the block was no longer significant ($p$ > 0.05).

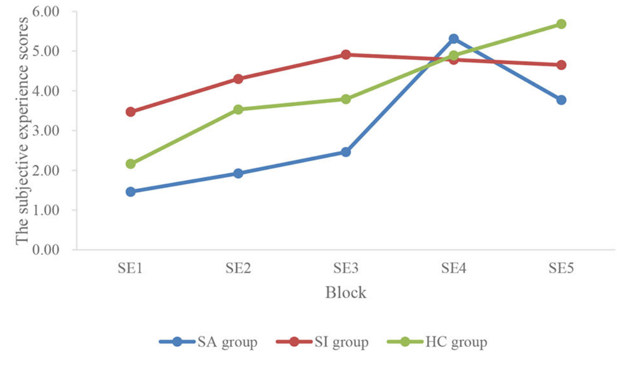


**FIGURE 2 |** Average subjective experience scores in five blocks of different groups.

## Conscious Knowledge

### Subjective Experience

The subjective experience scores of three groups were analyzed with 3 (group) × 5 (block) repeated measurement ANOVA. The main effect of the block was significant ($F = 7.23$, $p < 0.01$, $\eta_p^2 = 0.12$), which showed that the score of subjective experience was higher as time goes on (see **Figure 2**). The main effect of the group was not significant ($p > 0.05$), and the interaction effect between group and module was not significant ($p > 0.05$). Finally, the main effect of the block was no longer significant when taking age as the covariate.

The relationships between subjective experience and net scores of five blocks are shown in **Table 3** in the whole subjects. There were significant correlations between IGT net scores of five blocks and the subjective experience scores.

### General Conscious Knowledge

To improve the power of the statistical test, the subjects with levels 0 and 1 were integrated into one group. Therefore, we tested the net score differences between 0–1 and 2 levels of overall explicit understanding. The Chi-square test showed that there was no significant difference among the groups at different levels of conscious knowledge ($p > 0.05$; **Table 4**).

We analyzed the relationship between the levels of general explicit understanding and net scores of the IGT in all participants. The results of $t$-test showed that the difference between the IGT net scores of subjects with level 2 ($n = 38$, $M = 38.32$, $SD = 56.39$) and those of subjects with level 0–1 ($n = 16$, $M = 6.56$, $SD = 69.34$) was close to significant ($p = 0.08$). There was no significant difference in IGT net scores between different levels of general explicit understanding in any of the three groups ($p > 0.05$).

We used the score of the fifth subjective experience (SE5) as another index of explicit understanding. No significant differences were found in SE5 among the three groups ($p > 0.05$; **Table 5**). The correlation analysis showed that SE5 was positively correlated with IGT net scores in all subjects ($r = 0.19$, $p < 0.05$; **Figure 3**). In addition, group analysis showed that there was a significant correlation in the SA group between SE5 and IGT net scores ($r = 0.70$, $p < 0.05$; **Figure 4**), but no such correlation was found in the other two groups.

## Psychophysiological Measure

The result of 3 (group) × 2 (type) repeated measurement ANOVA indicated that the main effect of card type was significant ($F = 15.10$, $p < 0.01$, $\eta_p^2 = 0.23$), i.e., the anticipatory SCRs of the disadvantageous decks were significantly higher than that of advantageous decks (**Figure 5**). However, the main effect of the group was not significant ($p > 0.05$), and the interaction was not found ($p > 0.05$). The main effect of card type was no more significant after including the age as a covariate in the analysis ($p > 0.05$).

The results of ANOVA showed that there was no significant difference in the autonomic response among the three groups (see **Table 6**). There was a significant positive correlation between the autonomic response and IGT net scores in all subjects ($r = 0.27$, $p < 0.05$; **Figure 6**). Group analysis showed that there were significant positive correlations between IGT net scores and the autonomic response ($r = 0.55$, $p < 0.05$; **Figure 7**), and between the anticipatory SCRs of disadvantageous decks and IGT net scores ($r = 0.45$, $p = 0.05$) in the HC group.

## The Relationship of Explicit and Implicit Systems

There were no significant correlations between the SE5 and SCRs, such as, autonomic response ($p > 0.05$), anticipatory SCRs for the disadvantageous decks ($p > 0.05$), and the advantageous decks ($p > 0.05$).

## Relationships Between Decision-Making Performance and Clinical and Personality Variables

There were no significant correlations between IGT net scores and the score of depression ($p > 0.05$), suicide ideation ($p > 0.05$), state anxiety ($p > 0.05$), trait anxiety ($p > 0.05$), and six dimensions of emotional dysregulation ($p > 0.05$).

# DISCUSSION

To our knowledge, this is the first study to explore the influence of explicit knowledge and somatic markers on the decision-making performance of suicidal subjects. No significant differences were found among the three groups on IGT performance, explicit knowledge, and anticipatory SCRs. IGT performance was positively correlated with an index of explicit knowledge (SE5) in suicide attempters and all the subjects, while it was positively correlated with the index of anticipatory SCRs (the difference between the disadvantageous and advantageous decks) in healthy controls and all the subjects.

Behavior results showed that there was no significant difference among the three groups in IGT net scores, and the result was still the same after controlling for age, which was contrary to Hypothesis 1. This result was consistent with the findings of Gorlyn et al. (2013) and Deisenhammer et al. (2018). Gorlyn et al. (2013) found no significant difference between

**TABLE 3 |** Correlations between subjective experience scores and IGT net scores of five blocks in the whole subjects.

| | SE1 | SE2 | SE3 | SE4 | SE5 |
|---|---|---|---|---|---|
| Block 1 | 0.38** | – | – | – | – |
| Block 2 | 0.41** | 0.51** | – | – | – |
| Block 3 | 0.10 | 0.38** | 0.47** | – | – |
| Block 4 | 0.18 | 0.28* | 0.49** | 0.39** | – |
| Block 5 | 0.14 | 0.22 | 0.36** | 0.39** | 0.40** |

*$^{**}p < 0.01$. $^{*}p < 0.05$.*

**TABLE 4 |** Distribution of subjects in overall explicit understanding level.

| | Levels 0 and 1 | Level 2 | $\chi^2$ | *p* |
|---|---|---|---|---|
| SA group | 6 | 6 | 3.20 | 0.20 |
| SI group | 6 | 17 | | |
| HC group | 4 | 15 | | |

*One subject in the SA group had an absence of explicit understanding data.*

**TABLE 5 |** The score of SE5 in three groups.

| | *N* | *M* | *SD* | *F* | *p* |
|---|---|---|---|---|---|
| SA group | 13 | 3.78 | 3.49 | 1.24 | 0.30 |
| SI group | 23 | 4.65 | 3.64 | | |
| HC group | 19 | 5.68 | 3.13 | | |

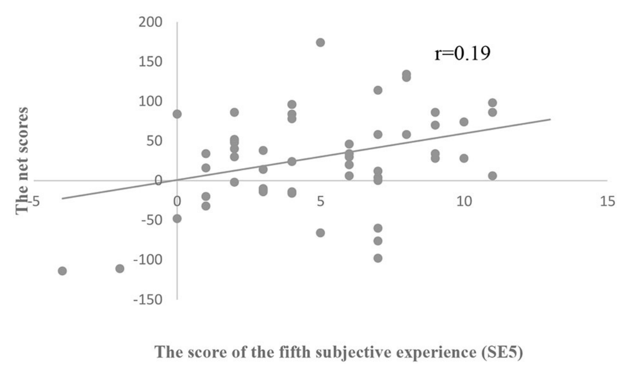


**FIGURE 3 |** Scatterplot of the relationship between IGT net scores and SE5 among all participants.

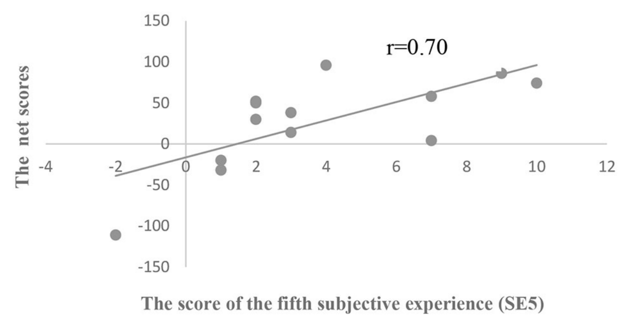


**FIGURE 4 |** Scatterplot of the relationship between IGT net scores and SE5 in the SA group.

the suicide attempters with depression and control subjects, but violent suicide attempters performed worse in the IGT. Moreover, IGT net scores did not differ significantly among currently depressed suicide attempters, depressed in-patients without suicide behaviors, and healthy controls (Deisenhammer et al., 2018). However, more studies revealed that suicide attempters with mood disorders performed worse than affective and healthy control groups in decision-making tasks (Westheide et al., 2008; Malloy-Diniz et al., 2009; Jollant et al., 2010, 2013; Martino et al., 2011; Bridge et al., 2012). The possible explanations for the inconsistent results could be different sample sources and definitions of suicide attempts (Jollant et al., 2005; Gilbert et al., 2011). Most previous studies were conducted in clinical samples with mood disorders and other psychiatric diagnoses. However, the subjects of our study were recruited from a college students sample and only five subjects in the SA group had psychiatric diagnoses, which may result in a lower pathological level of the subjects. Decision-making deficit was also shown to be associated with major psychiatric disorders, such as normothymic bipolar disorder and depression (Jollant et al., 2007; Caceda et al., 2014). In most previous work, suicide attempts were defined as actual self-injury acts with some

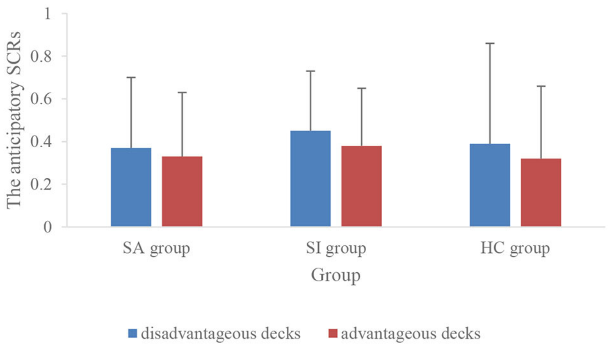


**FIGURE 5 |** The anticipatory SCRs of disadvantageous and advantageous decks in three groups.

intent to die (Jollant et al., 2005, 2010; Gilbert et al., 2011; Bridge et al., 2012). For example, in the study of Jollant et al. (2005), the definition of suicide attempts indicated that patients who exhibited only suicidal ideation or who threatened to commit suicide without actually taking action were not included. However, suicide attempts in our study, according to C-CASA, were defined as potential self-injurious behaviors with certain death intentions, which incorporated aborted ($n$/N = 5/13) and interrupted ($n$/N = 1/13). Moreover, decision-making deficit was found in suicide attempters with violent means rather than non-violent means (Jollant et al., 2005; Gorlyn et al., 2013). Suicide methods of the SA group in this study were all non-violent, such as drug overdose, wrist cutting, and so on, which may contribute to the non-significant result on decision-making performance between suicide attempters and other subjects.

Compared with the HC group, the decision-making performance of suicide ideators was not impaired, which was consistent with Hypothesis 2. There was no significant correlation between suicide ideation and decision-making performance in suicide ideators and all the subjects. There were only three previous studies that explored the decision-making performance of suicide ideators. Moreover, our findings were compatible with the results of Bridge et al. (2012) and Sheftall et al. (2015). For example, Sheftall et al. (2015) did not find group differences between the youths who had suicide ideation in the past 6 months and comparison subjects. However, the study from Westheide et al. (2008) found suicide attempters with current suicide ideation showed impaired decision-making, and suicide ideation was significantly associated with decision-making performance. Therefore, we still cannot conclude that whether there was a decision-making deficit in suicide ideators because of the small number of relative studies and the inconsistent results, which should be resolved in future studies.

In our study, conscious knowledge was indexed by subjective experience and general conscious knowledge. The score of subjective experience was gradually improved in all subjects. This result was replicated with previous studies, which showed that the level of explicit knowledge improved gradually as the decision-making task proceeded in the normal sample (Guillaume et al., 2009; Fernie and Tunney, 2013). There were no significant differences in both measures of explicit knowledge among the three groups. This appeared to show that the explicit system of suicide subjects was not damaged. The study by Jollant et al. (2013) is the first and the only previous study to explore the relationship of the explicit system and decision-making performance in suicide attempters with mood disorders. Their results showed no difference in the level of an explicit understanding of the IGT between suicide attempters with mood disorders and affective controls. It was compatible with our result, which showed that there was no difference in the explicit understanding level between healthy college controls and college suicide attempters with high cognitive levels. The electrophysiological results showed that anticipatory SCRs for disadvantageous decks (A and B) exceeded advantageous decks (C and D) in all subjects. This was in agreement with previous studies in healthy subjects (Wagar and Dixon, 2006; Guillaume et al., 2009; Mardaga and Hansenne, 2012; Yen et al., 2012). Disadvantageous decks induced greater anticipatory SCRs to help participants away from the unfavorable choices (Bechara et al., 1994; Bechara and Damasio, 2005; Sarchiapone et al., 2018). Unfortunately, this result was absent after the control of age. We did not find a significant difference among the three groups in the autonomic response, which might suggest no implicit system impairment in suicide attempters and suicide ideators. In addition, so far there was no previous study that explored whether there is somatic markers deficit in suicidal subjects.

Our correlation results showed that decision-making performance in all the subjects was correlated with explicit knowledge and somatic markers, and there was no correlation between them. Decision-making, therefore, seemed to be associated with the explicit and implicit systems, which is proved by studies conducted in healthy controls (Guillaume et al., 2009; Fernie and Tunney, 2013) and amnesic patients (Gutbrod et al., 2006). Furthermore, IGT net scores were associated with an index of explicit knowledge in suicide attempters and were correlated with the autonomic response of anticipatory SCRs in healthy controls, which implied that distinct strategies were applied in two groups to maintain a similar level of decision-making performance.

The correlations between decision-making performance and somatic markers in healthy controls were consistent with previous research (Carter and Pasqualini, 2004; Wagar and Dixon, 2006; Guillaume et al., 2009; Miu et al., 2012). Success on the IGT was positively correlated with the anticipatory SCRs within a healthy population (Carter and Pasqualini, 2004). Similar SCRs studies also found that overall anticipatory SCRs positively predicted IGT performance of healthy subjects (Wagar and Dixon, 2006; Guillaume et al., 2009; Mardaga and Hansenne, 2012). A meta-analysis by Simonovic et al. (2019) revealed a small-to-medium significant relationship between anticipatory SCRs and IGT performance, which supported the somatic marker hypothesis. Several EEG studies in healthy controls have demonstrated that there was a more negative potential (i.e., Decision Preceding Negativity, DPN) for disadvantageous deck anticipation in the right frontal region (Bianchin and Angrilli, 2011; Giustiniani et al., 2015). Moreover, some functional MRI (fMRI) studies in normal subjects also showed that

**TABLE 6 |** The anticipatory SCRs of disadvantageous and advantageous decks and the autonomic response in three groups.

| | Disadvantageous decks | | Advantageous decks | | Autonomic response | | *F* | *p* |
|---|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | | |
| SA group | 0.37 | 0.33 | 0.33 | 0.30 | 0.04 | 0.08 | 0.30 | 0.74 |
| SI group | 0.45 | 0.28 | 0.38 | 0.27 | 0.06 | 0.05 | | |
| HC group | 0.39 | 0.47 | 0.32 | 0.34 | 0.07 | 0.15 | | |

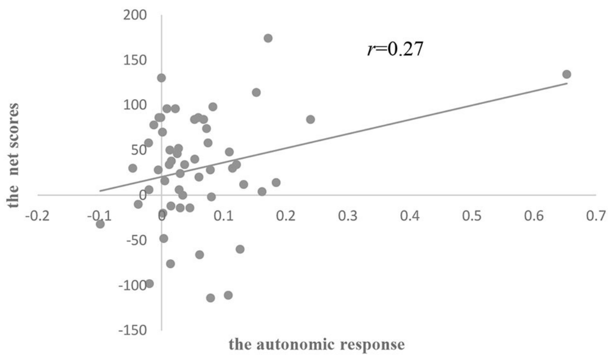


**FIGURE 6 |** Scatterplot of the relationship between IGT net scores and the autonomic response among all participants.

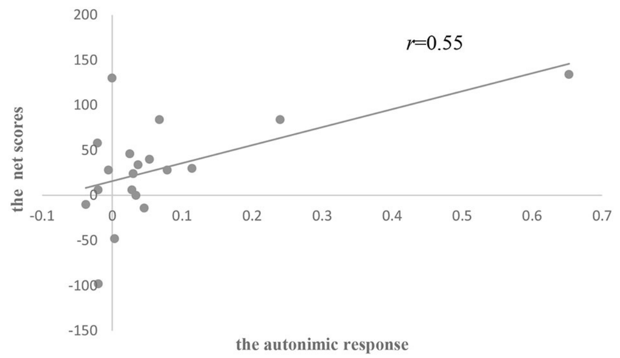


**FIGURE 7 |** Scatterplot of the relationship between IGT net scores and the autonomic response in the HC group.

IGT performance was positively correlated with the activation difference of selecting the unfavorable and the favorable in the ventral media prefrontal lobe (VMPFC, BA10; Fukui et al., 2005) and the left orbital frontal cortex (OFC, BA47; Lawrence et al., 2009). The VMPFC, especially including the OFC region, played a critical role in the process and encoded the outcome-value associations (Rangel et al., 2008; Poppa and Bechara, 2018), which are both in the somatic marker neural circuitry (Li et al., 2010a). However, disrupted VMPFC and OFC value encoding in people with suicide behaviors had been confirmed (Richard-Devantoy et al., 2014; Dombrovski and Hallquist, 2017). Jollant et al. (2010) discovered decreased activation in OFC during risky vs. safe choices in suicide attempters when performing the IGT. Although no impairment of implicit system was found in suicidal subjects in our study, these biological findings could provide some evidence for the potential generation abnormalities of somatic markers in suicide attempters.

Jollant et al. (2013) noted that more explicit knowledge was linked to better IGT performance in healthy and affective controls, but not in suicide attempters. There was no significant IGT performance difference between those who reached or not reached an explicit understanding of suicide attempters. Suicide attempters showed a disconnection between what they know and what they do, and they had deficient use of explicit understanding with the possible impaired implicit system. Therefore, they speculated that the sufficient use of explicit knowledge may be insured when there is an efficient implicit system (Jollant et al., 2013). However, in another study, most post-graduate students had enough knowledge to guide IGT performance after 40 trials and no anticipatory SCRs difference between the bad and good decks in the period before acquiring the knowledge in the normal sample (Fernie and Tunney, 2013). This finding was inconsistent with Jollant et al. (2013) speculation, and the anticipatory SCRs did not show necessary to succeed in the IGT (Gutbrod et al., 2006). Therefore, our results seemed to indicate that, due to the possible difficulty of utilizing somatic markers, the college suicide attempters with high cognition depended more on their explicit knowledge and applied this compensatory strategy to decide as normally as healthy controls.

The limitations of this study should be noted. First, our sample of 36 suicidal individuals could be considered relatively small. It was ambiguous that the performance of suicide attempters in the IGT was on account of the suicide behaviors or the psychiatric symptoms. These results need to be further validated. Second, the influence process of the implicit and explicit systems on decision-making is still in dispute, and the somatic marker hypothesis has been questioned (Fernie and Tunney, 2013; Dong et al., 2016). More factors about the influence on the decision-making process should be discussed in the future. Finally, heart rate, event-related potentials, and other neuroimaging techniques with various strengths could measure the somatic state, which could provide more evidence to the neurophysiological mechanisms during decision-making (Xu and Huang, 2020).

In summary, this study sheds light on the different roles of somatic markers and explicit knowledge on the decision-making performance of healthy controls and suicide attempters. Decision-making in healthy controls was mainly affected by the somatic markers. While the suicide attempters seemed to apply a compensatory strategy by mostly utilizing explicit knowledge to perform as normally as healthy controls in the IGT.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of Tianjin University. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

LLW and JML wrote the manuscript and finished the statistical analysis. JML, HLL, and ZPW collected the data and made a preliminary data analysis. LY and LA contributed to the conception and design of the study. LA revised the manuscript. All authors contributed to the article and approved the submitted version.

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# Influence of the Manner of Information Presentation on Risky Choice

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We are constantly faced with decisive situations in which the options are not presented simultaneously. How the information of options is presented might influence the subsequent decision-making. For instance, presenting the information of options in an alternative- or dimension-wise manner may affect searching patterns and thus lead to different choices. In this study, the effects of this manner of information presentation on risky choice according to two experiments (Experiment 1, $N = 45$; Experiment 2, $N = 50$) are systematically examined. Specifically, two tasks with different presentation are conducted. Participants could search the information of one option (alternative-wise task) or dimension (dimension-wise task) for each time. Results revealed that the participants assigned in the alternative-wise task exhibited more choices consistent with expected value theory and took a longer decision time than those in the dimension-wise task. Moreover, the effect of task on choice was mediated by the direction of information search. These findings suggest a relationship between information search pattern and risky choice and allow for a better understanding of the mechanisms and processes involved in risky choice.

**Keywords: risky choice, information search, presentation manner, expected value maximization, attention allocation**

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## 1. INTRODUCTION

In our daily life, we are always faced with decisive situations in which the options are not presented simultaneously. Thus, examining the effect of information presentation manner on decision-making is important. Imagine the following two scenarios:

*Scenario 1: Your investment counselor shows you two investment plans. She tells you, "In one plan, you can earn $1,000 with 90% probability. In the other plan, you can earn $1,500 with 70% probability." Which plan will you choose?*
*Scenario 2: Your investment counselor shows you two investment plans. She tells you, "In one plan, you can earn $1,000, and in the other plan you can earn $1,500. The probabilities of earning money in the two plans are 90% and 70%." Which plan will you choose?*

Although the information on risky options is exactly the same in the two scenarios and the decision time is unlimited, the manner of presentation may lead to different risky choices. In this study, we aim to examine the effect of presentation manner on risky choices.

In the field of decision-making under risk, mainstream theories commonly predict that for each option, individuals will weigh the value of each outcome by some function of probability, sum up all weighted values, and select the option that offers the highest overall value (Edwards, 1954; Payne and Braunstein, 1978; Basili and Chateauneuf, 2011). Prominent theories of risky choices, such as expected value (EV) theory and cumulative prospect theory (CPT) (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992), all belong to the family of expectation models. For instance, EV theory assumes that individuals calculate the expected value for each option and choose the option with the highest expected value. This weighting and adding process requires the integration of all available information on the options, wherein complex computations and an *alternative-wise* information search are performed.

Other researchers proposed that people choose between risky options, relying on simplification heuristics, such as maximax heuristic and priority heuristic (Brandstätter et al., 2006). By following a heuristic process, people need not integrate information from all dimensions to reach a decision; rather, they usually rely on a single key dimension. The heuristic process requires the selective use of information on the options, wherein simple and ordinal comparisons and a *dimension-wise* information search pattern are applied. For instance, maximax heuristic assumes that individuals identify the maximum outcome of each option and choose the option with the highest monetary payoff. Empirical evidence demonstrates that different models fit certain risky tasks (Pachur et al., 2014; Barrafrem and Hausfeld, 2019; Schoemann et al., 2019), indicating that people may apply various strategies in executing different tasks.

In this study, the alternative-/dimension-wise presentation of risky information is hypothesized to influence the risky choices of individuals. Previous research showed that information search patterns correlate with the decision strategy. In risky decisions from experience, Hills and Hertwig (2010) found that individuals who switch less between options are more likely to apply the EV maximization strategy. In intertemporal choices, Reeck et al. (2017) found that manipulating the ease of dimension-wise information search patterns had a causal influence on the intertemporal choice of individuals. In their experiment, a participant moves the mouse over a relevant box to view that piece of information, and then, the information contained within that box is revealed. Researchers made either dimension- or alternative-wise transitions relatively more difficult by introducing a 1,000 ms delay between the time when a participant's cursor entered a box and the time when the information in that box was revealed. All other transitions caused the box to open immediately. The results showed that the information search of participants is affected by the manipulation, and thus, their intertemporal choices are biased. Following the same logic, in this study, presenting risky information in an alternative- or dimension-wise manner is hypothesized to manipulate the ease of information search strategies, thus promoting the choices predicted by alternative- or dimension-wise models. Therefore, we hypothesize that the risky choices of participants would be affected by the presentation manner of information.

In this study, we conducted two experiments to examine the effect of presentation manner on the risky choices of individuals. With the use of a within-subject design, the participants were asked to complete two tasks in which they could search the risky information on a desktop screen and make a choice. Given that previous work highlighted the effect of task complexity (e.g., the number of alternatives and dimensions) in determining the decision strategy adopted by individuals (Payne, 1976), we focus on the simplest type of risky options (i.e., each option contains one non-zero outcome and one corresponding probability). In the alternative-wise task, participants could press one key on the keyboard to search the information on one option and press another key to search the information on the other option. Similarly, in the dimension-wise task, information search is performed in a dimension-wise manner.

We hypothesize that participants in the alternative-wise task are more likely to adopt the alternative-wise expectation strategies, whereas participants in the dimension-wise task are more likely to adopt the dimension-wise heuristic strategies. Substantial studies have revealed that compared with the heuristic strategies, the expectation strategies elicit more choices predicted by EV theory (Rao et al., 2015; Ashby et al., 2018) and longer decision time (Su et al., 2013). Hence, the following hypothesis is posed:

> $H_1$: Participants in the alternative-wise task will make more EV-consistent choices and take a longer decision time than in the dimension-wise task.

We also hypothesize that the direction of information search varied between the alternative-wise and dimension-wise tasks. The participants in the alternative-wise task are prompted to adopt the alternative-wise information search, whereas those in the dimension-wise task are more likely to adopt the dimension-wise information search. Previous evidence showed that EV strategy elicits more alternative-wise information search compared with heuristic strategy (Pachur et al., 2013; Su et al., 2013). We thus infer that participants in the alternative-wise task will show more alternative-wise information search than in the dimension-wise task and thus make more EV-consistent choices. Therefore, our second hypothesis for this study is derived.

> $H_2$: The effect of task on EV-consistent choice will be mediated by the direction of information search.

In this study, two experiments tested the hypotheses above. In Experiment 1, we tested $H_1$ by examining whether the differences in choices and decision times between the alternative-/dimension-wise tasks exist. In Experiment 2, we tested the mediation effect of the direction of information search. Data from the experiments reported in this study and **Supplementary Material** are publicly available *via* the Open Science Framework (https://osf.io/s29x6/).

## 2. EXPERIMENT 1

In Experiment 1, we examined the effect of presentation manner on the decision-making of individuals in simple binary gambles. In the experiment, each option contained one outcome and one corresponding probability. For the alternative-wise task, participants were instructed to press keys to search the information of one option for each time. For the dimension-wise task, participants were instructed to press keys to search the information on one dimension (i.e., outcome dimension or probability dimension) for each time.

## 2.1. Method

### 2.1.1. Participants

Forty-five college students ($M_{age} = 21.0 \pm 1.8$; 60% women) were recruited from a university's human subject pool to participate in this experiment. All participants had normal or corrected-to-normal vision and provided written informed consent prior to the experiment. The participants received 20 yuan (RMB; approximately US$2.9) in cash for participating and an additional amount (1–10 yuan; approximately US$0.1–$1.5) based on their performance during the experiment.

### 2.1.2. Stimuli and Experimental Task

The stimuli consisted of 60 pairs of randomly generated risky options. All the options involved gains only, and no dominating options existed. The outcomes ranged from 1 to 99 yuan, and the probabilities ranged from 1 to 98% (see **Supplementary Table 1**). The probabilities were presented to the left of the outcomes. The positions of the options were counterbalanced, that is, the riskier option (gaining a greater amount with lower probability) was either on the top or the bottom. Stimuli were presented on a 17-inch LCD monitor controlled by a Dell PC with a display resolution of 1,024 × 768 pixels and a refresh rate of 60 Hz.

Two risky choice tasks were performed in this experiment, namely, alternative- and dimension-wise tasks, both of which were completed on a computer. Participants were instructed to search the information of risky options freely and choose their preferred options. In the alternative-wise task, participants were asked to search the information of one option for each time. In the dimension-wise task, participants were asked to search the information of one dimension (i.e., probability dimension or outcome dimension) each time. Each participant performed the two tasks, but performed only one task on a given day, with an interval of no <3 days between the two tasks. The order of the tasks was counterbalanced across participants. The two tasks contained the same 60 pairs of gambles. With 60 trials per condition and 45 participants, the number of data points per condition exceeded that recommended by Brysbaert and Stevens (2018).

To incentivize their cooperation further, the participants were told that one choice would be randomly selected at the end of the experiment to be treated as a real choice, with the relevant outcomes determined by a computer program. All possible outcomes (1–99 yuan) were discounted at a rate of 0.1. Therefore, the participants would receive an additional incentive (1–10 yuan) to their 20-yuan payment for participating in the experiment.

### 2.1.3. Procedure

In each task, the participants first consented to take part in the experiment. Thereafter, they were given instructions about the experiment, and two practice trials were allowed to familiarize the participants with the task. The testing session contained 60 trials, the order of which was counterbalanced across participants. The 60 trials were divided into two blocks, with each block containing 30 trials. Participants were permitted to take a 1–2 min break after finishing each block.

At the beginning of each trial, a fixation disc was presented at the center of the display. Then, the participants were asked to press F and J on the keyboard to search the information of the risky options. In the alternative-wise task, the participants pressed F and J to search the information of options A and B, respectively. Likewise, in the dimension-wise task, the participants pressed F or J to search the information of the probability or outcome dimension, respectively. No time limit was set for searching information, and the participants were asked to press the space key to prompt the decision screen after they finished searching. Subsequently, the participants indicated their choice by pressing F (a decision for option A) or J (a decision for option B). After each participant responded, a 1,000 ms interval (with a blank screen) was shown before the next trial began. **Figure 1** presents the trial procedure and timing.

### 2.1.4. Strategy Classification

To examine the effect of presentation manner on the choices of individuals, we modeled the choices of the participants by using the EV strategy and the maximax heuristic strategy. According to the EV strategy, the weighted (by probability) outcomes of each option are integrated, and the option with the highest expected value is chosen. According to the maximax strategy, the options are compared according to their maximum outcomes, and the option with the more attractive maximum outcome is chosen. We used EV and maximax to model the choices separately for the risky choices of the participants in the two tasks. Using a maximum likelihood approach, we classified each participant to the strategy with the best fit (Pachur et al., 2014; Suter et al., 2016). Specifically, for each participant *i*, the goodness of fit of strategy *k* across *N* pairs of risky options was determined as

$$G_{i,k}^2 = -2\sum_{j}^{N} ln[f_j(y)] \tag{1}$$

where $f_j(y)$ represents the probability with which the strategy predicts an individual choice $y$ in risky choice $j$. If option A was chosen, then $f_j(y)$ was the probability that the strategy predicted the choice of option A over option B, $p_j$(A, B). If option B was chosen, then $f_j(y)$ was the probability that the strategy predicted the choice of option B, 1–$p_j$(A, B). $p_j$(A, B) was defined using the softmax choice rule

$$p_j(A, B) = \frac{e^{\varphi \cdot V(A)}}{e^{\varphi \cdot V(A)} + e^{\varphi \cdot V(B)}} \tag{2}$$

where for EV, the subjective valuations of options A and B, $V$(A) and $V$(B), were defined as $V(\text{A}) = x_\text{A} \times p_\text{A}$ and $V(\text{B}) = x_\text{B} \times p_\text{B}$, respectively (with $x$ and $p$ being the outcome and probability of

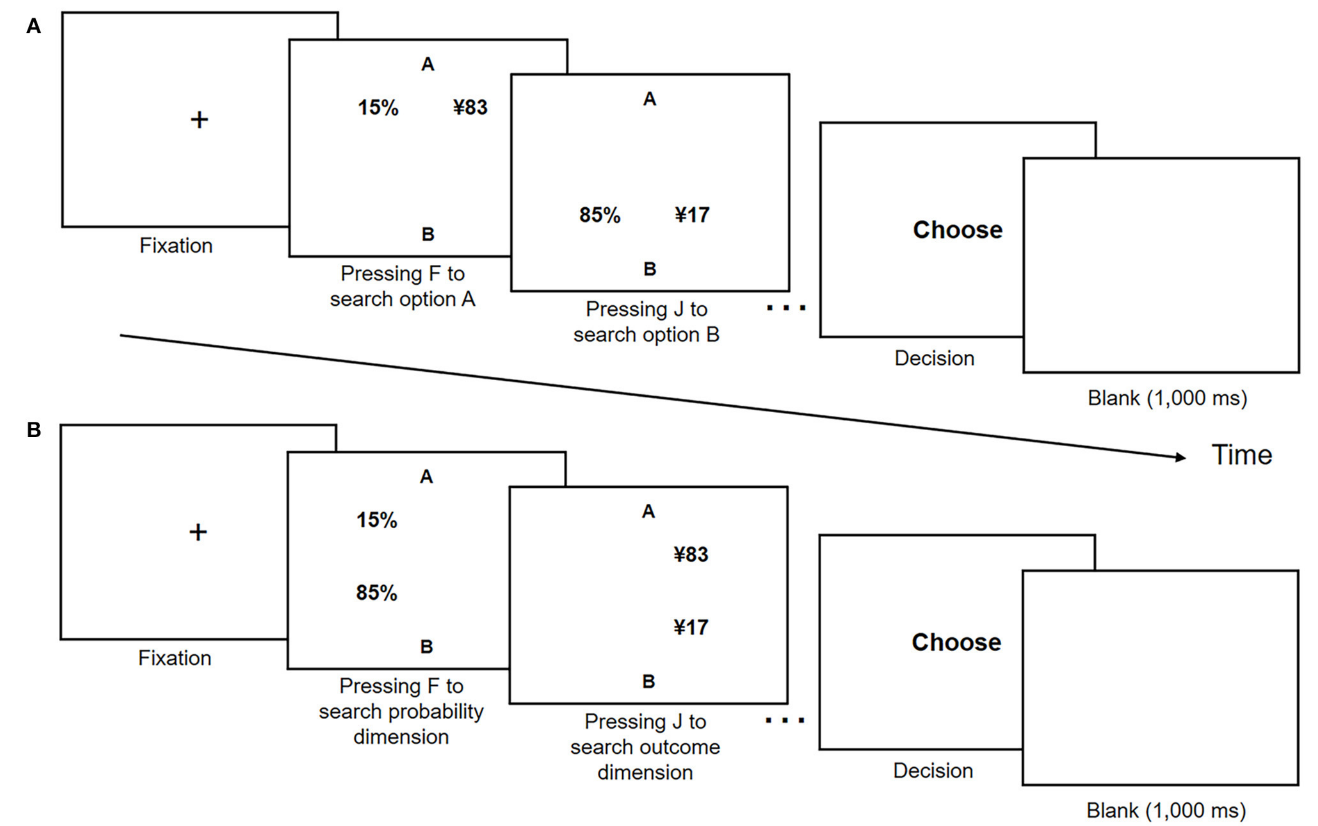


**FIGURE 1 |** Trial procedure and timing in **(A)** alternative- and **(B)** dimension-wise tasks in Experiment 1.

the nonzero outcomes of the option, respectively); for maximax, they were defined as $V(\text{A}) = x_{\text{A}}$ and $V(\text{B}) = x_{\text{B}}$. The adjustable parameter $\varphi$ is a choice sensitivity parameter (estimated for each participant) that specifies how sensitive the predicted $p_j$ is to differences in the subjective valuation of the gambles. Participants were classified as following the strategy with the best fit (i.e., lowest $G^2$). If the best-fitting strategy $G^2$ equalled (or was higher than) the value of $G^2$ under random choice (i.e., with $p[\text{A, B}] = 0.5$), then the individual was classified as "guessing or using another strategy."

### 2.1.5. Data Analysis

We used mixed-effect models with random effects of participant and item (pairs of options) to analyze our data by using the *lme4* and *lmerTest* packages in the R statistical environment (Bates et al., 2015; Kuznetsova et al., 2017). Treating the participant and item as random factors allowed us to generalize our findings beyond specific participants and items in this study (Baayen et al., 2008; Judd et al., 2012).

## 2.2. Results

### 2.2.1. Choices

We found that the participants made the same choice in the two tasks in 78% of the cases. To examine the effect of the task on individuals' EV maximization strategy, we conducted a mixed-effect logistic regression that predicted the EV-consistent choice by task, including the random effects for participant and item. We found that the task was a significant factor in predicting an increased likelihood of EV-consistent choice, $b = 0.28$, $\text{CI}_{95\%} = [0.14, 0.42]$, OR $= 1.32$, $\text{CI}_{95\%} = [1.15, 1.52]$, $z = 3.84$, $p < 0.001$. The results indicated that the dimension-wise presentation manner made participants less likely to adopt the EV maximization strategy, thus supporting $H_1$.

### 2.2.2. Strategy Classification

We modeled the participant choices by using the EV strategy and the maximax heuristic strategy. The best-fitting parameter values and the respective model fits of the strategies are reported in **Supplementary Table 3**. The distribution of participants classified as EV or maximax strategy is shown in **Figure 2A**. Although more participants were classified as following EV in the alternative-wise task (96%) than in the dimension-wise task (87%), the difference did not reach significance level: $z = 1.48$, $p = 0.069$.

### 2.2.3. Decision Time

Response times (the period from searching the information until the decision prompt and then log-transformed) were examined with a mixed-effect linear regression, including the fixed effects of task (1 = alternative-wise; 0 = dimension-wise), the EV

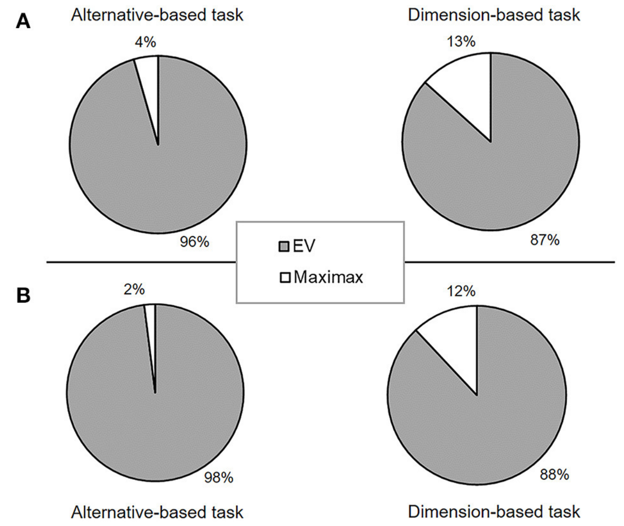


**FIGURE 2 |** Proportion of participants classified as following the EV strategy and the maximax heuristic strategy, classified separately for the alternative-wise and the dimension-wise tasks in **(A)** Experiment 1 and **(B)** Experiment 2, respectively.

difference (the absolute value of the difference between the expected values of two options), the outcome difference (the absolute value of the difference between the outcomes of two options), and the random effects of participant and item. We found that the decision time in the alternative-wise task ($M = 4.88$ s, $CI_{95\%} = [4.72, 5.04]$) was longer than that in the dimension-wise task ($M = 4.13$ s, $CI_{95\%} = [4.01, 4.25]$), $b = 0.16$, $CI_{95\%} = [0.14, 0.19]$, $t = 11.86$, $p < 0.001$. The EV difference was a significant predictor that predicted the decision time, $b = -0.006$, $CI_{95\%} = [-0.007, -0.004]$, $t = -7.32$, $p < 0.001$. The outcome difference cannot significantly predict the decision time, $b = -0.00$, $CI_{95\%} = [-0.001, 0.001]$, $t = -0.73$, $p = 0.472$.

# 3. EXPERIMENT 2

In Experiment 1, we found that the presentation manner affects the simple risky choice of the individuals. In Experiment 2, we used eye-tracking technology to further test the mediation effect of the direction of information search.

## 3.1. Method

### 3.1.1. Participants

We calculated the sample size based on the result of EV-consistent choice in Experiment 1 by using *lmmpower* function for *longpower* package in R (Donohue and Edland, 2016), with a power of 0.95 and an $\alpha$ error probability of 0.05. The results indicated that 2,703 samples were needed, suggesting that approximately 45 participants were needed for this experiment. Fifty college students ($M_{age} = 23.9 \pm 3.6$; 42% women) participated in the current experiment. All participants had normal or corrected-to-normal vision and provided written informed consent prior to the experiment. The participants received 20 yuan in cash for participating, and an additional amount (1–10 yuan) based on their performance during the experiment.

### 3.1.2. Apparatus

The eye movements of the participants were recorded by using the EyeLink 1000 Plus desk-mounted eye tracker (SR Research, Ontario, Canada) with the eye position sampled at 1,000 Hz. The visual display was presented on a 17-inch LCD monitor (with a refresh rate of 60 Hz) controlled by a Dell PC. The screen resolution was $1,024 \times 768$ pixels. A chin rest was used to minimize head movements and to maintain the distance between the eyes and monitor at 58 cm. When viewed from this distance, the screen subtended a visual angle of 36° horizontally and 29° vertically. Participants viewed the stimuli with both eyes, but eye movement data were collected from the right eye only. Participants responded during the experiment by pressing keys on a keyboard.

### 3.1.3. Stimuli and Experimental Task

The stimuli were composed of 60 pairs of gambles, which were generated randomly by a computer. Different from Experiment 1, all the pairs of gambles were selected such that the maximax heuristic and EV strategy predicted opposite choices. The position of the options was counterbalanced. The values of each option (i.e., outcomes and probabilities) were presented in Arial font at a 1.3° visual angle. The (horizontal/vertical) center-to-center distance between any two values was greater than 5°, which ensured that the values were fixated properly and prevented peripheral identification of an adjacent value during fixation (Rayner, 1998, 2009).

Similar to Experiment 1, two tasks were performed in this experiment: alternative- and dimension-wise tasks.

### 3.1.4. Procedure

After giving their consent, the participants were informed about the experiment and given a brief description of the apparatus. A five-point calibration and validation procedure was used. The maximum error of validation was 0.5° in the visual angle. After the initial calibration, two practice trials were conducted to allow the participants to familiarize themselves with the task. The testing session contained 60 trials, the order of which was counterbalanced across participants. The 60 trials were divided into two blocks, with each block containing 30 trials. Participants were permitted to take a 1–2 min break after finishing each block.

At the beginning of each trial, a fixation disc was presented at the center of the display. This disc also served as a drift check for the eye tracker. When fixation on that disc was registered, the participants were asked to press F and J on the keyboard to search the information of the risky options. In the alternative-wise task, the participants pressed F and J to search the information of options A and B, respectively. Likewise, in the dimension-wise task, the participants pressed F or J to search the information of the probability or outcome dimension, respectively. No time limit was set for searching information, and the participants were asked to press the space key to prompt the decision screen after they finished searching. Subsequently, the participants indicated their choice by pressing F (a decision for option A) or J (a decision for option B). After each participant responded, a 1,000 ms interval (with a blank screen) was shown before the next trial began. **Figure 3** presents the trial procedure and timing.

#### 3.1.5. Pre-processing of the Eye-Tracking Data

The collected eye movement data were analyzed by using EyeLink Data Viewer (SR Research, Ontario, Canada). Four non-overlapping, identically sized ($16.2 \times 11.5^{\circ}$ visual angle) rectangular regions of interest around each piece of information (i.e., the outcomes and probabilities) were defined. Fixations were described as periods of a relatively stable gaze between two saccades, and fixations shorter than 50 ms were excluded from the analyses.

#### 3.1.6. Search Measure Index

To evaluate the overall search direction of information acquisition, we employed the search measure (SM) index proposed by Böckenholt and Hynan (1994) to combine the transition percentages into an aggregate measure

$$SM = \frac{\sqrt{N}[\frac{AD}{N}(r_a - r_d) - (D - A)]}{\sqrt{A^2(D-1) + D^2(A-1)}} \quad (3)$$

where $A$ and $D$ denote the number of options and the number of dimensions, respectively (i.e., in this experiment, $A = 2$, $D = 2$); $r_a$ and $r_d$ denote the number of alternative-wise transitions and dimension-wise transitions, respectively, and $N$ denotes the number of total transitions. The predominance of alternative-wise transitions increases with an increasing value of SM index (Su et al., 2013). A negative value of SM index indicates a predominantly dimension-wise search, and a positive value indicates a predominantly alternative-wise search (Pachur et al., 2013).

### 3.2. Results

#### 3.2.1. Choices

We found that in 82% of the cases, the participants made the same choice in the two tasks. To examine the effect of the task on individuals' EV maximization strategy, we performed a mixed-effect logistic regression that predicted the EV-consistent choice by task, including the random effects of participant and item. We found that task was a significant factor that predicted an increased likelihood of EV-consistent choice, $b = 0.73$, $CI_{95\%} = [0.56, 0.90]$, $OR = 2.08$, $CI_{95\%} = [1.76, 2.45]$, $z = 8.59$, $p < 0.001$. The results of EV-consistent choice indicated that the dimension-wise search manner made people less likely to adopt the EV maximization strategy. Thus, $H_1$ was supported.

#### 3.2.2. Strategy Classification

Similar to Experiment 1, we classified each participant to the strategy with the best fit. The distribution of participants classified as EV or maximax strategy is shown in **Figure 2B**. The results revealed that more participants were classified as following the EV strategy in the alternative-wise task (98%) than in the dimension-wise task (88%), $z = 1.96$, $p = 0.025$. The results suggest that the difference between the alternative-wise task and dimension-wise task may, at least in part, be attributed to people's use of different strategies.

#### 3.2.3. Decision Time

Similar to Experiment 1, decision times were examined with a mixed-effect linear regression, including the fixed effects of task, EV difference, outcome difference, and the random effects of participant and item. We found that the decision time in the alternative-wise task ($M = 4.32$ s, $CI_{95\%} = [4.17, 4.48]$) was longer than that in the dimension-wise task ($M = 3.86$ s, $CI_{95\%} = [3.76, 3.96]$), $b = 0.08$, $CI_{95\%} = [0.05, 0.10]$, $t = 6.31$, $p < 0.001$. The EV difference was a significant predictor that predicted the decision time, $b = -0.009$, $CI_{95\%} = [-0.011, -0.007]$, $t = -8.06$, $p < 0.001$. The outcome difference cannot significantly predict the decision time, $b = -0.00$, $CI_{95\%} = [-0.002, 0.001]$, $t = -0.44$, $p = 0.665$.

#### 3.2.4. Search Measure Index

We found that the SM index in the alternative-wise task ($M = 1.87$, $CI_{95\%} = [1.83, 1.91]$) was significantly greater than that in the dimension-wise task ($M = -0.98$, $CI_{95\%} = [-1.01, -0.94]$), $b = 2.85$, $CI_{95\%} = [2.80, 2.90]$, $t = 109.03$, $p < 0.001$.

To test whether the effect of task on EV-consistent choice was mediated by the SM index, we used the GAMLj module (Gallucci, 2019) in jamovi (jamovi project, 2019) to perform mediation analysis. We hypothesized that compared to the dimension-wise task, the alternative-wise task increased the alternative-wise information search, thereby leading to more EV-consistent choices.

The task (independent variable) was entered as a dummy-coded variable (1 = the alternative-wise task; 0 = the dimension-wise task), EV-consistent choice (dependent variable) was entered as a dummy-coded variable (1 = choose the option with higher EV; 0 = choose the option with lower EV), and the SM index was the mediator. The numbers of participants and items were controlled as covariates. We generated 95% CI on the basis of 5,000 bootstrap samples.

**Figure 4** shows the results of the mediation analysis through the SM index. The total and direct effects of task on the EV-consistent choice were $c = 0.07$, $CI_{95\%} = [0.05, 0.09]$, $z = 7.15$, $p < 0.001$ and $c' = -0.06$, $CI_{95\%} = [-0.09, -0.02]$, $z = -3.50$, $p < 0.001$, respectively, and the total indirect effect through the SM index (mediator) was $ab = 0.12$, $CI_{95\%} = [0.10, 0.15]$, $z = 10.04$, and $p < 0.001$. The results of mediation analysis supported $H_2$.

## 4. DISCUSSION AND CONCLUSION

In this study, we conducted two experiments to systematically examine the effects of the manner of information presentation on simple binary gambles (Experiment 1) and further examine the mediation effect of direction of information search (Experiment 2). The results revealed that (1) compared with the participants in the dimension-wise task, those who performed the alternative-wise task were more likely to adopt the EV maximization strategy; (2) the decision time in the alternative-wise task was greater than that in the dimension-wise task; and (3) participants in the alternative-wise task showed more alternative-wise information search and thus exhibited more EV-consistent choices than in the dimension-wise task.

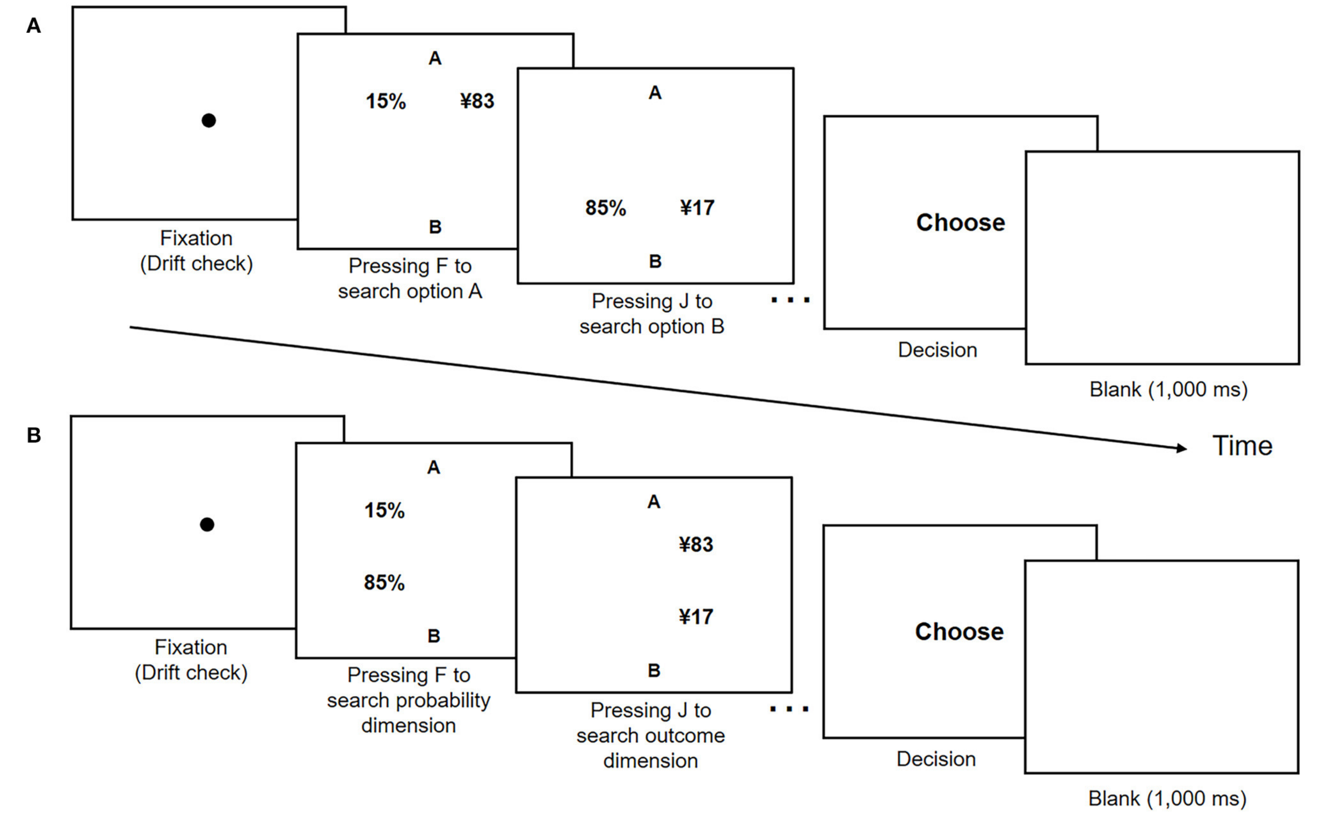


**FIGURE 3 |** Trial procedure and timing in **(A)** alternative- and **(B)** dimension-wise tasks in Experiment 2. Each trial began with each participant fixing their gaze at the middle of the screen. After registering their response, these participants were shown a blank screen at a 1,000 ms interval before proceeding to the next trial.

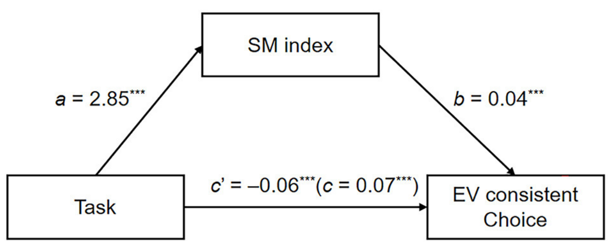


**FIGURE 4 |** Results of the mediation analysis of the SM index in Experiment 2. The indirect effect is the product of coefficients *a* and *b*. The coefficients in parentheses are the total effect (i.e., sum of indirect and direct effects). $^{***}p < 0.001$.

Our findings indicate that the decision strategies during risky choices can be affected by the presentation manner. Specifically, the participants showed more EV-consistent choices and required a longer decision time in the alternative-wise task than in the dimension-wise task in both experiments. EV theory usually assumes a complex computation process and predicts a longer decision time (Su et al., 2013). Therefore, the results suggest that individuals may use multiple strategies in risky choices and shift between these strategies as a function of task and strategic variability, which is consistent with previous studies (Venkatraman et al., 2009; Ashby et al., 2018; Popovic et al., 2019).

We found that most of the participants were classified as following the EV strategy (92% in Experiment 1 and 93% in Experiment 2). One reason for this result might be that we focused on the simple binary gambles (i.e., between pairs of options, each consisting of a probability $p$ to win amount $x$) in this study. In this condition, the participants had sufficient cognitive resources to execute the EV maximization calculation. This condition can also explain why we found that the EV difference can significantly predict the decision time but the outcome difference cannot. Previous research that used simple binary gambles also found that the alternative-wise process models decisively outperformed dimension-wise ones in accounting for choices and decision times (Glickman et al., 2019), which is consistent with our findings.

A detail that is worth noting is that although the expectation models can be interpreted as describing strategies that adopt the weighting and adding process (Pachur et al., 2013; Su et al., 2013), someone may argue that the interpretation of expectation models as process models may sometimes be overly simplistic. However, a recent work revealed that the parameters of CPT can reflect selective attention allocation (Pachur et al., 2018), indicating that the as-if model can also reflect the characteristics of information processing. Glöckner and Betsch (2008) also argued that the weighting and adding process can be accomplished by the intuitive system and provided process evidence.

The findings of this study have implications on the cognitive process during risky decision-making. We found that the alternative-/dimension-wise tasks influenced participants' direction of information search, thus leading to different choices. The alternative-wise task promotes alternative-wise comparisons and thus enhances the possibility of adopting the EV maximization strategy. Similarly, the dimension-wise task promotes dimension-wise comparisons and hampers the possibility of using the EV maximization strategy. Substantial research has shown that the risky choices of the individuals in different tasks are always accompanied by a varied SM index value (Pachur et al., 2013, 2014; Su et al., 2013; Pfeiffer et al., 2014), which reflects the direction of information search. The finding that the SM index mediated the effect of task on choices indicates that the direction of transitions plays an important role in the process during risky choice.

The above results add to the wealth of evidence that supports the causal link between information process and risky decision-making. Previous studies focused on the perspective of attention allocation and revealed that both alternative-wise and dimension-wise relative attention are associated with subsequent risky choice (Fiedler and Glöckner, 2012; Pachur et al., 2013; Brandstätter and Körner, 2014; Stewart et al., 2015). Sui et al. (2020) found that the manipulations on both alternative-wise and dimension-wise relative attention can have a causal influence on risky choices. This study revealed that the manipulation on the ease of strategies can also influence the risky choice of the individuals, providing a new perspective to examine the causal link. Future studies may consider developing a new paradigm to manipulate the strategies in a straightforward manner to bias the risky choice of the individuals.

Our results have implications for risky decision-making in real-world contexts. The findings, which indicated that risky decisions can be affected by a convenient manipulation of presentation manner, suggests a potential application of an intervention improving an individual decision-making by using a similar presentation set. Looking back at the aforementioned scenarios, if the investment counselor expects you to make a choice wise on expectation theories, then she should present the information in an alternative-wise manner to help in your decision-making.

We acknowledge some constraints in this study. First, the probabilities were always presented to the left of the outcomes in both experiments. Given that decision-makers generally prefer to read from left to right (Orquin and Loose, 2013), the unbalanced position of outcomes/probabilities on the left/right may lead to more attention on the probabilities. Future studies may consider presenting the gambles in an ellipsoid display format (Glöckner and Herbold, 2011) to eliminate this confounding effect. Second, this study used a within-subject design and did not employ a control condition. Future studies are encouraged to include a control task, for example, a task in which the information of options can be shown on the screen simultaneously, thus enabling the effect of representation manner to be evaluated exactly.

In conclusion, this study indicates that the manipulation on the manner of information presentation can systematically influence the subsequent risky choices.

## DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/**Supplementary Material**.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Review Board of Psychology of Nankai University. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

H-ZL and Z-HW conceived and designed this study and wrote the paper. H-ZL, PL, and Z-HW designed experimental stimuli and procedures. PL implemented experimental protocols and collected data. H-ZL and PL analyzed data. All authors contributed to the article and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

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ORIGINAL RESEARCH
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# Do Emotions Benefit Investment Decisions? Anticipatory Emotion and Investment Decisions in Non-professional Investors

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Increasing financial trading performance is big business. A lingering question within academia and industry concerns whether emotions improve or degrade trading performance. In this study, 30 participants distributed hypothetical wealth between a share (a risk) and the bank (paying a small, sure, gain) within four trading games. Skin Conductance Response was measured while playing the games to measure anticipatory emotion, a covert emotion signal that impacts decision-making. Anticipatory emotion was significantly associated with trading performance but the direction of the correlation was dependent upon the share's movement. Thus, anticipatory emotion is neither wholly "good" nor "bad" for trading; instead, the relationship is context-dependent. This is one of the first studies exploring the association between anticipatory emotion and trading behaviour using trading games within an experimentally rigorous environment. Our findings elucidate the relationship between anticipatory emotion and financial decision-making and have applications for improving trading performance in novice and expert traders.

**Keywords: anticipatory emotion, skin conductance, skin conductance response, investment, trading, finance**

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## INTRODUCTION

The key to being a successful trader is a huge business. While many academics argue that emotions degrade trading performance (Gray, 1999; Lerner and Keltner, 2001; Lo et al., 2005; Lucey and Dowling, 2005; Shiv, et al., 2005; Schunk and Betsch, 2006), there are those who contest that emotions have, instead, a positive impact (Ackert et al., 2003; Ackert and Deaves, 2010).

Neoclassical economics has eschewed the investigation of emotions in favour of portraying decision-makers as "rational" and non-emotional. Newer developments in behavioural economics and emotional finance have mostly relied on a psycho-analytic approach to understand the effect of emotions on trading decisions. In their research into the dot.com bubble of the twenty-first century, Taffler and Tuckett (2005) pioneered the field of emotional finance by introducing Freud's theory of Psychoanalysis and "phantasy" objects to investment behaviour. Taffler and Tuckett theorised that a range of unconscious emotions dictate investors' decision-making, more than knowledge of company fundamentals or future growth potential. For example, continual growth in share price is associated with excitement and overconfidence in investors which is, in turn, associated with "herding" behaviour in groups of investors, creating market bubbles (Taffler and Tuckett, 2005; Shefrin, 2007; Taffler et al., 2017). When the bubble "bursts", high levels of negatively valenced emotions such as regret and guilt further impact investment decisions, typically promoting risk avoidance (Taffler and Tuckett, 2005; Taffler et al., 2017). Thus, unconscious emotion significantly impacts trading behaviour.

Empirical research within psychology indicates that unconscious anticipatory emotions are critical components of a functional decision-making system (Bechara et al., 1997, 2001). Anticipatory emotions input physiological (somatic) signals of emotion into whatever decisions we are currently making, with a traditional view that they provide "gut feelings" that push us towards particular alternatives within the decision (Bechara et al., 2005). Dysfunction of brain areas involved in the formation of anticipatory emotions impacts decision-making whereby individuals may struggle to choose between seemingly simple alternatives (Damasio, 2008).

Although a critical component of decision-making, the role of anticipatory emotions remains under debate (Dunn et al., 2006). Davis et al. (2009) posit that anticipatory emotions, rather than being a rapid, coarse, signal of value or risk (the traditional, "emotions-as-input" perspective), they represent a relatively slower process (Hinson et al., 2006) interacting with cognitive processes in response to uncertainty or contextual novelty and signal a readiness to learn (the "emotions-as-output" perspective). Otto et al. (2014) support the emotions-as-output perspective, showing that anticipatory emotions interact with cognitive processes and provide reflection on choice consequences. Whatever the stance on anticipatory emotions, there is agreement that they are important signals integrated into current decision strategies. It is important to note that there appears to be a "dark side" of anticipatory emotion, where high levels of unconscious emotion can degrade choice behaviour (Shiv et al., 2005). Given the case that anticipatory emotions are not comprehensively "good" nor "bad" for investment decisions, what can we learn about the relationship between anticipatory emotion and risk-aversion/−seeking in a range of trading environments?

This study addresses this question utilising a neuroeconomic approach to measure anticipatory emotion, *via* recordings of Skin conductance response (SCR), in multiple trading games with varying share patterns. Participants with varying levels of trading experience decided how to allocate wealth between a safe, but low paying, option (the "bank"), or a potentially higher-risk, but higher-payoff, option (the share).

## MATERIALS AND METHODS

### Participants

Thirty participants (18 male) were recruited with a mean age of 27.13 (*S.D.* 7.66) years. Twenty-four participants were students at the University of Bath with the remaining six participants being University employees. Preliminary analyses revealed no systematic differences between student and nonstudent responses; thus they were combined in all analyses. Eighteen participants classified themselves as Caucasian European, three as Asian, one as Afro-Caribbean and two classified their ethnicity as "other." Eight participants reported that they had played the stock market previously. Out of these eight participants, one played daily, one did not play daily but several times per week, two played several times per month but not weekly and four played several times per year but not monthly.

Participants received £5 remuneration for their participation. To promote a motivation to perform well on the task there were also prizes of £70, £20 and £10 for the individuals who obtained the highest, second highest, and third highest overall percentage return on investment, respectively, (calculated over all games). Informed written consent from all participants was obtained. The study was approved by the Psychology Research Ethics Committee at the University of Bath.

A power analysis was performed to check the appropriateness of the sample size using the results from the multilevel analysis between anticipatory SCR and returned trial-by-trial as due to the sensitivity of the test this stage would demand the highest sample size. G*Power 3.1.5 (Faul et al., 2007) was used to calculate power. Based upon an $R^2$ of.22 (taken from stage 1 of the analysis, see *Data Analysis* section), we computed that a sample of 30 participants yielded a power of 0.88, thus the sample size is appropriate.

### Material and Apparatus

The materials required for the experiment comprised of four stock market games (henceforth shortened to "stock games"). Physiological data were collected using a BIOPAC MP 150 system with a 500-Hz sampling rate. SCR activity was measured using a constant voltage (0.5 V) with Ag-AgCl electrodes attached to the distal phalanx of the middle and index finger of the non-dominant hand. Standardisation was achieved *via* the following steps; the SCR signal was low-pass filtered through the amplifier (1.0 Hz) and high-pass filtered (0.05 Hz) to extract the phasic SCR. A threshold of 0.02 microsiemens (μS) was used. Anticipatory SCR was extracted between the 3 s before a click to move to the next trial and 2 s after the start of the trial. SCRs are slow-wave functions and this window was used to allow capture of the peak amplitude of an anticipatory SCR that crossed the 0.02μS threshold (Dawson et al., 2011). Data were acquired in a quiet room controlled at room temperature. AcqKnowledge (version 4.3) analysis software and SPSS (v. 22) were used.

To explore the valence of emotion experienced within each game the Positive and Negative Affect Scale (PANAS) was given to all participants (Watson et al., 1988). The PANAS is a 20-item self-report questionnaire. Participants report to what level they feel 10 positive and 10 negative adjectives during the stock game that they had just experienced.

Participants were presented with four different computerised stock games. Participants were initially instructed that they had inherited £20,000, half in stocks and half in cash. Over a 10-year period (represented by 10 sequentially presented trials), they were to decide the amount they wished to invest in stock and the amount they would like to save as cash. The participants were told that their goal was to make as much money overall. In their first trial, they earned 2% interest on the cash and earned or lost money on the stocks dependent on its current price. Visual and descriptive information as to the behaviour of the stock and the amount of money they made in stocks, cash and overall was provided for each trial (see **Figure 1** for an example of one trial and pathways from each game). Stock game 1 followed an "n-shaped" stock market fluctuation, stock game 2 a "u-shaped" stock market scenario, stock game 3 an "upward" fluctuation and stock game 4 a "range trading" scenario (**Figure 1**). Participants could respond in their own time within each trial. When the participants clicked to move onto the next trial it was immediately shown. There was a non-linear relationship between risk aversion and return on initial investment such that those who are highly risk-seeking or risk-averse will not perform as well as those at a mid-point of risk aversion (Fairchild et al., 2016).

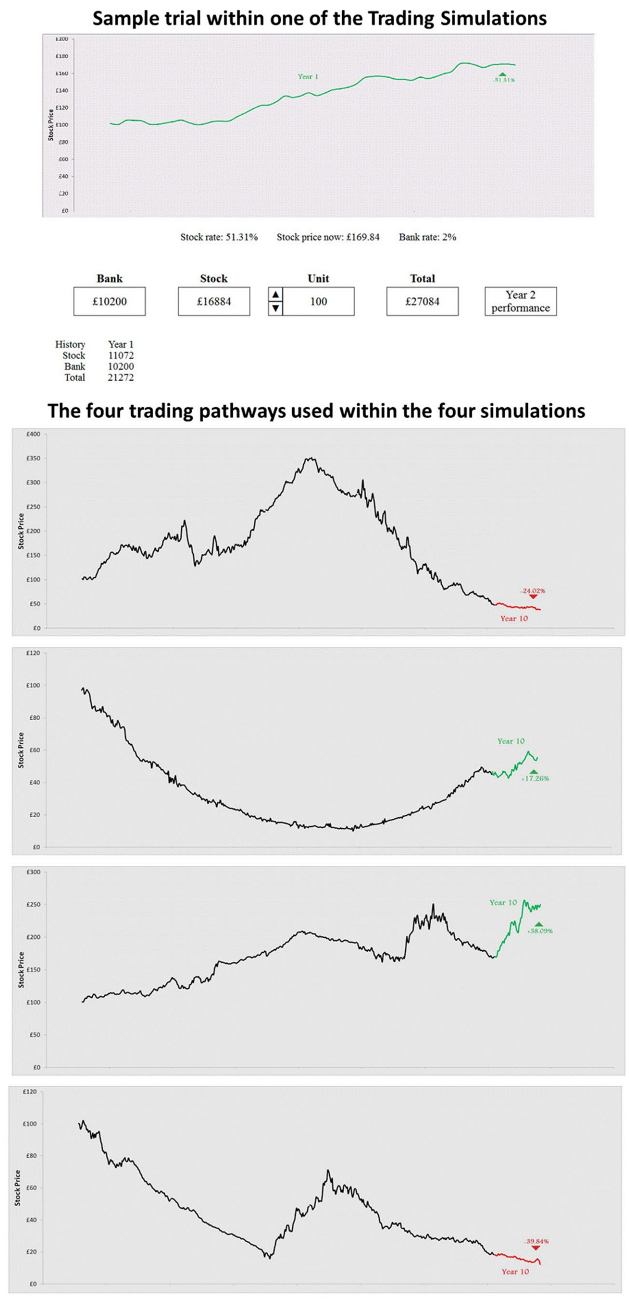


**FIGURE 1** | Screenshot of one trial from a stock market game and the share pathways used in the four games.

## Procedure

Each participant first read an information sheet and gave written consent to participate. They answered a demographic questionnaire providing information pertaining to their age, sex, gender, ethnicity, educational level, degree enrolled upon (if applicable) and if they trade in stock markets and, if so, the frequency of engagement during a typical month. Participants also completed the PANAS to measure initial emotional status.

Each participant was connected to the BIOPAC to measure SCR. After fitting electrodes to their non-dominant hand, participants were instructed to keep that hand still to avoid movement artefacts within the SCR waveform. A practice stock game was presented to the participant, to assess that they had fully comprehended the task and instructions. Participants subsequently started their first stock game. The order of presentation for all four stock games was randomised between participants to prevent order effects. Participants were given the PANAS after each game and instructed to rate themselves as to their emotional experience during the stock game that they had just completed. Once the participant had finished all four stock games they were verbally debriefed.

## Data Analysis

The variables of interest related to performance were the returns (i.e. profit or loss) that each individual made and anticipatory SCR. It is pertinent to explore returns as they tell us about whether the general trend on an individual's choice behaviour was to make a profit or loss.

For investigations into anticipatory emotion, the anticipatory SCR for each trial was associated with performance on the following trial, therefore, in each game, there were nine data points. SCR data are commonly positively skewed so a close look at the structure of the data was warranted. Any SCR values of zero (due to not reaching threshold for occurrence of a SCR) were removed from the data to avoid artificial "pushing" of the data into an extreme positive skew. Data were explored with and without outliers removed (*via* a 25/75% confidence interval threshold). There were no notable differences in skewness and kurtosis values between the two datasets so the original dataset was used in order to increase the amount of data analysed.

In order to ascertain the valence of the anticipatory emotion experienced by participants in each trend PANAS responses were coded into responses to adjectives that had a positive valence and those that had a negative valence. This gave scores on both valence for each trend. Residual PANAS scores were calculated by subtracting the value from the initial PANAS in order to control for each participant's emotional state before playing the games. These eight

**TABLE 1 |** Performance measures for each stock game.

| | Trend 1 | | Trend 2 | | Trend 3 | | Trend 4 | |
|---|---|---|---|---|---|---|---|---|
| | **Mean** | ***SD*** | **Mean** | ***SD*** | **Mean** | ***SD*** | **Mean** | ***SD*** |
| Average return on original endowment | −5.28% | 5.44% | 5.83% | 3.66% | 5.38% | 1.46% | −5.46% | 6.16% |
| Total trading volume | £49,963.46 | £31,312.61 | £17,195.87 | £22,496.61 | £35,970.06 | £23,791.26 | £13,823.91 | £9,423.69 |
| Average trading volume in each period | £5,551.50 | £7,849.88 | £1,878.83 | £6,222.53 | £3,904.71 | £5,488.05 | £1,513.55 | £2,664.54 |
| Return of "perfect" trader on original endowment | 13.96% | – | 13.67% | – | 13.40% | – | 11.25% | – |

*SD stands for standard deviation. The "perfect" trader is a fictitious trader who invests all money into shares when the share price subsequently increases and invests all money into the bank when the share price subsequently decreases.*

scores were entered into a 2×4 repeated-measures ANOVA to test whether there were differences in the valence of emotion experienced within each trend and between trends.

## RESULTS

### Relationship Between Anticipatory SCR and Returns Analysed Trial-by-Trial

**Table 1** shows performance measures within each of the trends. This table shows that trends 1 and 4 were associated, on average, with losses in return, while trends 2 and 3 were associated with more overall gain on participants' initial endowments.

Multilevel modelling (panel data) was used to correlate anticipatory emotion with return at each time point in each game. Return in this analysis was calculated as the percentage gain or loss in one trial *vs.* the previous. Multilevel modelling permitted the exploration of how anticipatory emotion was associated with decision-making within each time point compared to aggregating the data, permitting a fine-grained analysis of investor behaviour. **Figure 2** shows the mean SCR and percentage return per trial in all four games.

For game 1 (n-shaped), greater anticipatory SCR was associated (an almost significant correlation) with improved performance, OR (odds ratio) = 0.03, $p=0.06$, $R^2=0.001$. This means that when experiencing n-shaped trends greater levels of anticipatory SCR is associated with small, but potentially meaningful, improvements in investment performance. In game 2, there was a significant inverse correlation between anticipatory SCR and returns per trial, OR = −0.18, $p=0.039$, $R^2=0.22$. There was no significant correlation between returns and SCR in game 3, OR = 0.09, $p=0.43$, $R^2=0.003$, and game 4, OR = 0.03, $p=0.77$, $R^2=0.0004$.

### Exploration of Anticipatory Emotion Within Upward or Downward Share Sub-trends Within Games

Upward and downward trends in games 1 and 2 were extracted, and multilevel analysis of the data was performed as in the above section. This was conducted in order to explore whether performance improvements/degradations could be associated with simple linear responses to upward or downward trends or whether it was a response to the amalgamation of upward and downward trends in each game. There were no significant correlations between anticipatory SCR and return in any of the sub-trends, suggesting that performance improvements/degradations seen in the n-shaped and u-shaped trends were not down to a simple response to upward/downward trends but a response to the trend as a whole.

### The Effect of a Previous Outcome for an Individual on Anticipatory Emotion for a Subsequent Choice

To investigate how the outcome from a previous investment choice is associated with anticipatory emotion for a subsequent investment choice we used multi-level modelling to correlate the amount of return following a choice (which would be a value of a gain or loss) shown at the start of a trial with the SCR within the anticipatory window at the end of the same trial (i.e. anticipatory emotion associated with choice after feedback has been processed). For each game, we assessed those outcomes that ended in gain and, separately, those that ended in loss. Anticipatory emotion was not significantly correlated with preceding gain or loss amount, thus anticipatory emotion appears yoked to the current decision event and not previously experienced gains or losses.

### Overall, Consciously Reported, Emotional Reaction to Each Simulation

Mean residual PANAS scores separated by game and emotional valence are shown in **Table 2**. There was no significant difference in the level of positive, compared to negative, emotion reported after the games, $F(1,29)=1.67$, $p=0.21$, $\eta^2=05$. The magnitude of emotion reported after each game was also, overall, not significantly different, $F(3,87)=1.53$, $p=0.21$, $\eta^2=05$. There was a significant interaction, $F(3,87)=3.66$, $p=0.016$, $\eta^2=0.11$. The interaction arose from equal levels of reported emotion

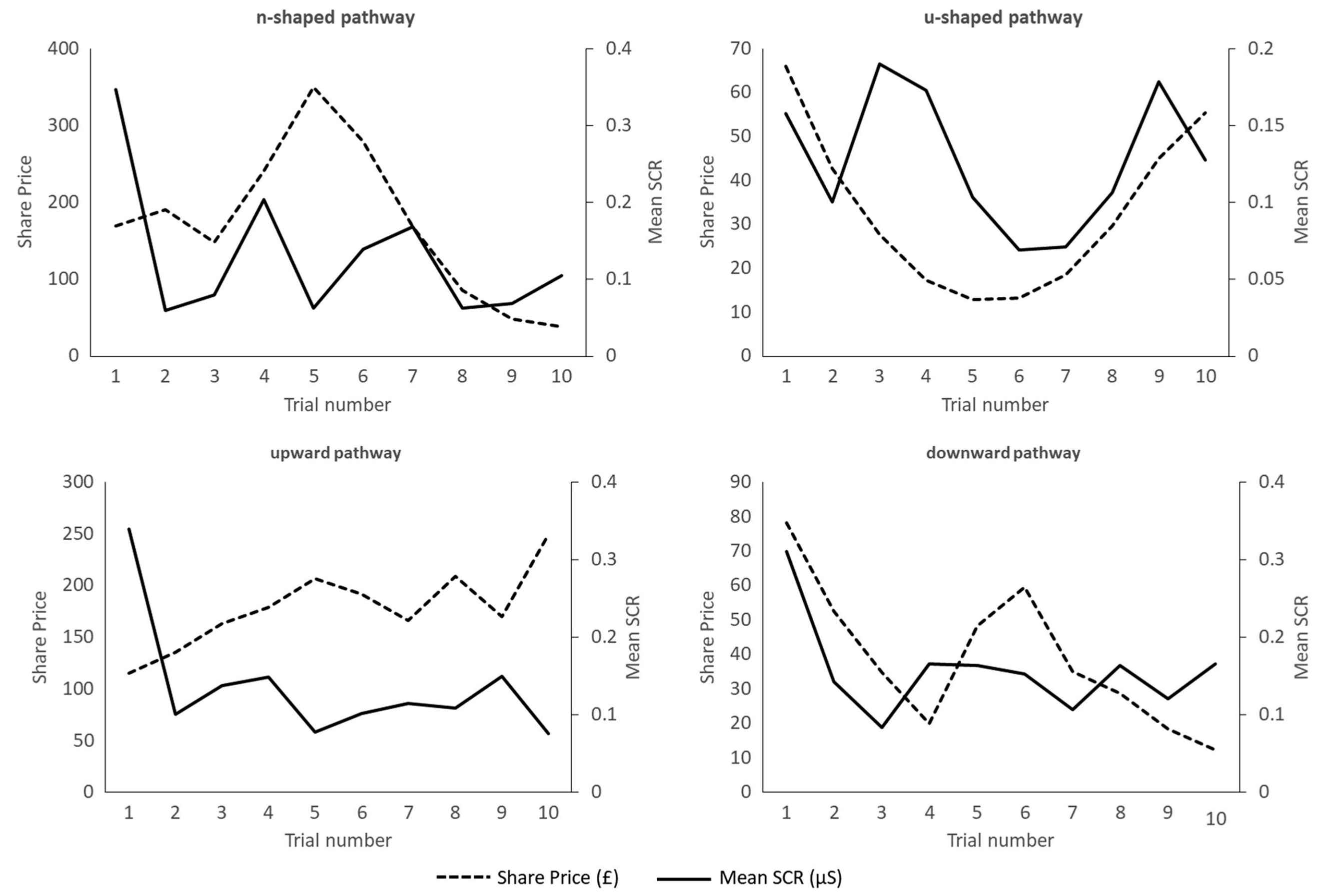


**FIGURE 2 |** Mean trial-by-trial skin conductance response (SCR) within each game plotted alongside share price.

**TABLE 2 |** Average residual PANAS scores for each game.

| | | Mean | 95% Confidence interval |
|---|---|---|---|
| Positive valence | Trend 1 | 0.73 | 2.11 |
| | Trend 2 | −2.37 | 2.17 |
| | Trend 3 | −1.73 | 2.54 |
| | Trend 4 | −0.13 | 2.04 |
| Negative valence | Trend 1 | −2.97 | 1.89 |
| | Trend 2 | −2.20 | 2.60 |
| | Trend 3 | −1.70 | 1.50 |
| | Trend 4 | −2.73 | 1.73 |

*Residual scores were calculated by subtracting the value of reported positive/negative valence emotion after each game and subtracting it from the baseline positive/negative PANAS score, respectively, reported before the participant played the games.*

in each valence in games 2 and 3 but much higher levels of negative compared to positive consciously reported emotion in games 1 and 4 (**Figure 3**). N.B. Significant results from simple effects are shown ($* = p < 0.05$; $** = p < 0.001$). Effects shown at the top of the figure relate to positive valence and that on the bottom refers to negative valence.

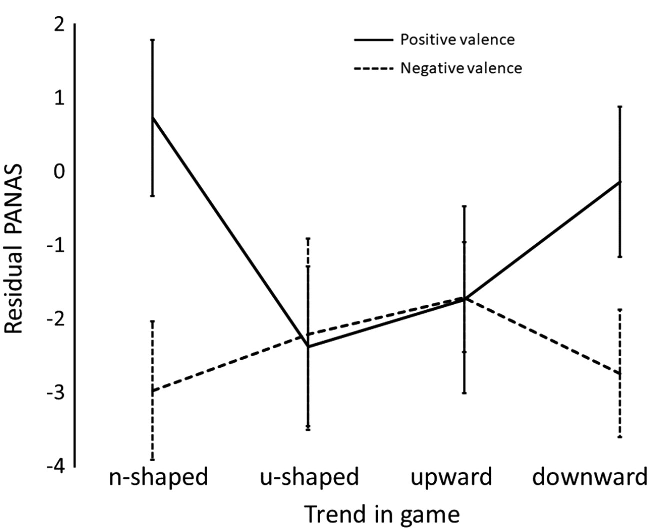


**FIGURE 3 |** Mean positive and negatively valence residual positive and negative affect scale (PANAS) scores within each game. Error bars show 95% confidence intervals.

## DISCUSSION

The key finding within this study is that the relationship between anticipatory emotion and choice behaviour is dependent on context, namely the share movement. In our games, trading gains acquired within an n-shaped share trend were associated with higher levels of anticipatory emotion, but in a u-shaped trend, gains were associated with lower levels of anticipatory emotion.

Our findings that the association between anticipatory emotion and trading performance in context-dependent is supported by Shiv et al. (2005). In this study, patients with damage to the ventromedial frontal cortex, who exhibit blunted anticipatory SCRs, and healthy participants were gifted $20 and given 20 opportunities to invest subsequent $1 portions of that money into a 50/50 gamble between losing $1 or winning $2.50. Expected utility demands that the best option is to gamble with all $1 portions. However, compared to 79% of patients who gambled, only 58% of healthy participants gambled. For healthy decision-makers, an injection of emotion into the decision as to whether to gamble led to a heightened level of risk aversion. This further supports the conclusion that anticipatory emotions will not lead to broad improvements in performance. Our study is novel in that it extends this finding to richer games of trading behaviour.

We are significantly more likely to be risk-averse when outcomes are framed in terms of what we could gain compared to what could be lost (Kahneman and Tversky, 1979; Tversky and Kahneman, 1981). In the n-shaped frame, participants experience an upward (gain) trend followed by a downward (loss) trend. In the u-shaped trend, participants experience a downward (loss) trend followed by an upward (gain) trend. It is pertinent to note that returns commonly followed the share pattern in all games, so participants typically experienced gain or loss aligned with an increase or decrease in share price, respectively (**Figure 4**). The evidence for framing effects can be noted from the analysis of the PANAS whereby the patterns associated with increased losses, games 1 and 4, were

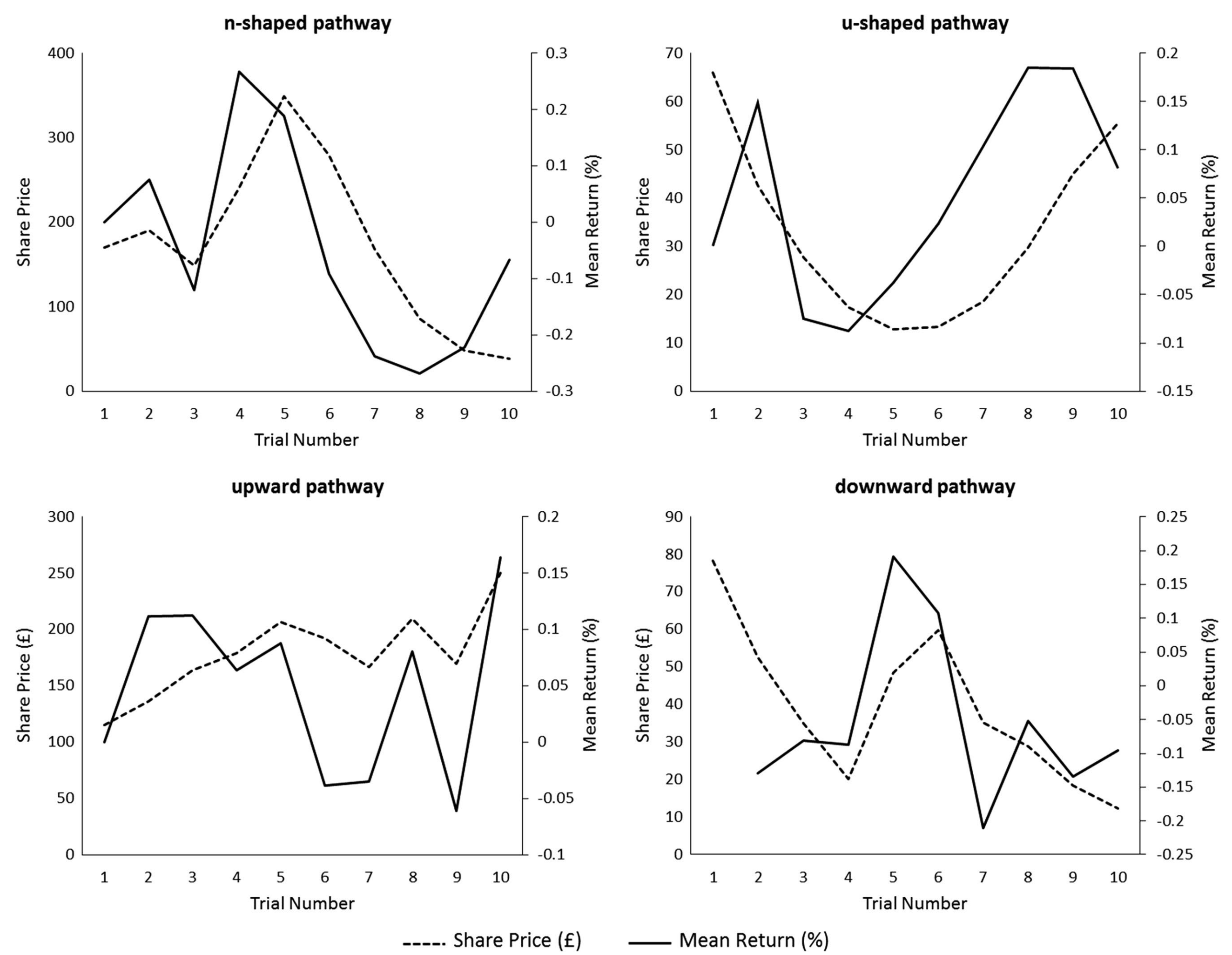


**FIGURE 4 |** Comparison of mean return on investment to the share pathway on the four stock market games.

associated with higher levels of negative compared to positive reported emotion compared to patterns associated with gains, games 2 and 3, where the magnitude of reported negative and positive emotions was approximately equal. Further evidence for framing effects can be taken from part 4 of the analysis where upward and downward sub-trends in the n- and u-shaped games were extracted. There was no simple linear effect between SCR and the sub-trends, and therefore, significant results are a product of the entire share pattern. This may explain the non-significant results for game 3 (upward share pattern) and game 4, (downward share pattern) in which, although framing effects may occur, they may not be as salient as in games 1 and 2. In games 1 and 2, the participant was faced with a situation where participants tended to have a "winning streak" followed by greater losses or by turning around a "losing streak" into a positive return. In games 3 and 4, the share pattern was either upward or downward in nearly all trials. Agency, or responsibility for outcomes based on a person's choices, may be higher in games 1 and 2 where a win changed to a loss, or *vice versa*, compared to games 3 and 4 where the decision-maker could predict with greater accuracy the share's pattern. This is potentially related to Zeelenberg et al. (1998) where participants experienced different emotions when they experienced greater agency in instances where their own decisions ended in loss (leading to a more visceral feeling of regret) *vs.* instances where there was no agency (leading to a less visceral feeling of disappointment). Findings may also be related to Duclos (2015) whereby the shape of a graphical trend of a stock price at the end of trading (upwards or downwards) would affect risk behaviour within subsequent investing decisions. Taken together, the shaping of the graph creates particular frames to which the investor differs to in response. An interesting next step may be to see whether the same results are found with different visual interfaces of the trading data. Previous research suggests that presentation of the same information in different visual formats, such as a graph or table, leads to differing levels of attention and processing of the financial information contained within (Ceravolo et al., 2019).

Emotions affect susceptibility to framing effects at a conscious (Covey, 2014; Lecheler et al., 2015) and unconscious (Ring, 2015) level. Furthermore, different frames engage different decision inputs within the brain. Hinvest et al. (2014) found that although a unitary brain system was involved in risky decisions regardless of framing, the frame itself elicited varying levels of activity in different neural regions within that system. Specifically, cognitive and emotional mechanisms have different levels of input into decision-making across different frames. Thus, in the current study, we feasibly conclude that the different share patterns (frames) receive different levels of input from cognitive and emotional systems leading to different patterns of emotional arousal and decision-making performance. In a potential future study, the feedback-related negativity (FRN) could be measured after each choice in the gain and loss portions of each trend to elucidate how emotion affects integration of feedback into future decision strategies as the strength of the FRN is impacted by current emotional state (Zhao et al., 2016; Gu et al., 2017).

Our results support the "emotions-as-output" hypothesis regarding the function of anticipatory emotion signals, albeit tentatively. The "emotions-as-input" hypothesis posits anticipatory SCR to be a signal of value that is based upon previous experience (Davis et al., 2009). The emotions-as-output hypothesis postulates that anticipatory SCR is a response to uncertainty and signals a need to learn. Our results indicate that anticipatory SCR is not predicted by the magnitude of gain or loss on a previous trial thus providing no evidence of a link between anticipatory SCR and previous outcomes refuting the assumptions of the emotions-as-input hypothesis.

Increasing the effectiveness of trading behaviour is big business, with a vast host of companies and websites aiming to offer support in developing an individual to make more money trading. The effect of emotions on trading performance is a common theme within this training. Many of these approaches are only loosely based on valid empirical research. Thus, research into how emotion effects trading performance is highly lucrative and essential to inform effective training. The current study supports and extends previous empirical work in this area. Lo and Repin (2002); Lo et al. (2005) and Fenton-O'Creevy et al. (2012) measured a range of psychophysiological signals, including SCR and heart rate variability, in professional traders in live trading environments and found that characteristics of the trading environment such as making positive returns and market volatility were associated with significant changes to arousal state. Interestingly, the arousal was positively associated with amount of trading experience (Lo and Repin, 2002). Experienced traders, it seems, do not "switch off" emotion but are more able to regulate their emotions and turn felt emotions into positive strategies (Fenton-O'Creevy et al., 2011, 2012). Our results extend the above findings though several means. Firstly, the current experiment explores the relationship between emotion and trading in a controlled, empirical, manner; a need highlighted by Lo and Repin (2002). Secondly, our study explores anticipatory emotions rather than those broadly felt alongside market events. This approach permits us to make inferences about how anticipatory emotion integrated into current decision strategies affect returns, a critical consideration if we wish to make inferences about how emotions are associated with actual trading decision performance. With the rise of online trading platforms (e.g. MetaTrader), a logical next step is to measure psychophysical and behavioural factors while investors engage with these platforms, potentially, with their own funds to further increase ecological validity. However, there are methodological hurdles to overcome in this approach, not least timing synchronisation between events shown *via* the online platform and psychophysical recording software and hardware.

Emotion regulation strategies designed to minimise variability in emotion have been found to increase the optimality of trading decisions (Fenton-O'Creevy et al., 2011; Hariharan et al., 2015). Our study adds novel ground to this research by suggesting that emotion regulation strategies should be yoked to the current share trend, e.g. an emotion regulation strategy when experiencing a downward trend may need to focus on maintaining high levels of arousal whereas maintaining a controlled low level of arousal will be important in an upward trend. The literature indicates that such rapid self-regulation is possible and effective in changing behaviour through simple cues, e.g. a simple command to "increase" "decrease" or "not regulate" emotions every 6.5 s with 2.5 s to "relax" between events, with participants choosing their own methods for doing so (Baur et al., 2015; Koch et al., 2018). Our study is a first step to understanding how emotion regulation strategies could be designed to be more effective. Our games are more controlled and shorter in duration to the typical real-world trading environment and further studies should present more trends and extend these games into providing longer test periods and testing of rapid self-regulation strategies.

Systems that measure SCR in traders and interrupt them when their level of arousal increases beyond a pre-determined threshold that signal high stress have been introduced as possible means of increasing trading performance (Dang et al., 2011). Our findings add to the literature to suggest that systems such as these could be extended to monitor the current share trend in addition to the individual's unconscious emotional status and align the two in such a way that performance is maximised using the enhanced emotion regulation strategies put forward in the previous paragraph. This would necessitate development of psycho/neuro-physical methods of measurement that can identify the valence and magnitude of emotion. There is emerging work that EEG could be used to identify whether an individual is in a positive or negative emotional state which, alongside SCR, would provide measurements of both an individual's emotional valence and level of arousal (Petrantonakis and Hadjileontiadis, 2010; Kim et al., 2013). Some of the Authors are already working in this area.

The current study has found that unconscious anticipatory emotion is associated with trading performance. Critically, the relationship between anticipatory emotion and performance is context-dependent, with greater anticipatory emotion associated with improved returns in some share patterns but negatively impact in other patterns due to a discovered link between anticipatory emotion and risk aversion. This work has implications for understanding the effect of emotions on trading performance and the design of emotional training regimes designed to improve financial returns from trading.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, upon request to the corresponding author.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Psychology Research Ethics Committee, University of Bath. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

NH led the development of the paper and co-supervised the research. RF co-supervised the research and contributed to drafts. MA led the analysis of data and contributed to drafts. MR collected data and contributed to analysis. All authors contributed to the article and approved the submitted version.

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