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Market mechanisms protect the vulnerable brain

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Abstract

Markets are mechanisms of social exchange, intended to facilitate trading. However, the question remains as to whether markets would help or hurt individuals with decision-making deficits, as is frequently encountered in the case of cognitive aging. Essential for predicting future gains and losses in monetary and social domains, the striatal nuclei in the brain undergo structural, neurochemical, and functional decline with age. We correlated the efficacy of market mechanisms with dorsal striatal decline in an aging population, by using market based trading in the context of the 2008 U.S Presidential Elections (primary cycle). Impaired decision-makers displayed higher prediction error (difference between their prediction and actual outcome). Lower *in vivo* caudate volume was also associated with higher prediction error. Importantly, market-based trading protected older adults with lower caudate volume to a greater extent from their own poorly calibrated predictions. Counterintuitive to the traditional public perception of the market as a fickle, risky proposition where vulnerable traders are most surely to be burned, we suggest that market-based mechanisms protect individuals with brain-based decision-making vulnerabilities.

Keywords

decision-making; aging; dopaminergic systems; markets; social neuroscience

1. Introduction

A general principle of human judgment and decision-making is that the brain is computationally limited (March & Simon, 1993, 1958). To deal with these computational limitations, humans adopt various heuristics (Tversky & Kahneman, 1974), to simplify their decision-making tasks, which are thus better characterized by bounded rationality. To maximize adaptive advantage in goal-oriented decisions, the brain adopts a computational

strategy of neuronally encoding prediction errors (the gap between a prediction and the actual outcome) to anticipate salient future outcomes (Schultz & Dickinson, 2000).

1.1 Prediction quality and the vulnerable brain

The brain's inherent computational limitations in decision-making are further exacerbated by certain vulnerabilities such as cognitive aging. Prediction quality (Schultz et al., 1997) among older adults gains importance in light of age-related cognitive compromise that affect decision-making acumen. Compensating for these deficits in complex decision-making, which can be manifest in spite of otherwise intact cognitive functioning (Denburg, Tranel & Bechara, 2005; Fein, McGillivray & Finn, 2007), is a huge challenge in aging societies, where healthy, normal, older adults are increasingly isolated (Cacioppo & Hawkley, 2003). Functional cognitive compromise has been well documented in the realm of decision-making where some older adults experience decline in real world complex decision-making (Denburg et al., 2005; Denburg, Recknor, Bechara & Tranel, 2006) related tasks in spite of otherwise normal cognitive functioning. In the real world context, older investors tend to display poor investment skills, in spite of superior investment knowledge (Korniotis & Kumar, 2011); and impaired decision-makers among cognitively healthy, older adults are easily susceptible to fraudulent advertisements (Denburg et al., 2005; Denburg et al., 2007). These ecological aspects of decision-making decline could make older adults prone to exploitation in situations of one-on-one negotiations in social and financial contexts. This is particularly relevant in aging societies that are undergoing demographic shifts with increasing number of older adults living in isolation (Cacioppo & Hawkley, 2003) and who can be taken advantage of.

In complex decision-making, reward prediction error recruits the striatum (D'Acremont, Lu, Li, Van der Linden & Bechara, 2009) and there are preliminary indications in dorsal striatal aging towards a positivity bias in anticipatory (Samanez-Larkin et al., 2007; Schott et al., 2007) as well as outcome signalling (Cox, Aizenstein & Fiez, 2008). This could make some older adults less accurate in their future predictions. Prediction accuracy could be undermined by the fact that the dorsal striatum, especially the caudate nucleus, undergoes significant volumetric reduction over the adult lifespan (Raz et al., 2005a; Raz, 2005b), with aging decline in striatal dopamine receptor availability (Bäckman, Nyberg, Lindenberger, Li & Farde, 2006), the key neural substrate for encoding prediction error (Schultz & Dickinson, 2000).

1.2 Prediction quality and the market

A market is a social mechanism that quintessentially involves prediction. Disparate knowledge held by various individuals is thus encoded into the trades and made available to all on a public platform by summarizing privately held information into one metric, viz. price (Smith, 2001). Thus, even though human agents who comprise a market suffer certain prediction limitations, the market at the aggregate performs better than the individual. An individual may incorporate cues in an idiosyncratic fashion, but given variability in cue utilization by agents, the market extracts different cues from different traders and aggregates them, resulting in a better-specified prediction model that enhances prediction accuracy.

A prediction market is a social mechanism wherein participants trade various alternative future scenarios – that is, shares are floated for various alternative outcomes and these shares are traded much like commodities on a stock market. Such markets have been found to frequently perform better than other instruments. Prior research has demonstrated that electronic prediction markets, such as the Iowa Electronic Market (IEM), outperform polls in accurately predicting political outcomes and movie box office receipts (Berg, Nelson & Reitz, 2008). This supposedly results from the fact that unlike poll participants, market

participants have a monetary incentive to truthfully reveal their beliefs. Since self-interest is on the line to a greater degree in the form of potential earnings, there is a greater chance of individuals expressing ‘true’ opinions, unclouded by wishful thinking or bias. Further, price is available to all, thus allowing updating of beliefs.

1.3 Markets as Protection for the Vulnerable

We suggest that the market can serve as a systemic form of protection for vulnerable populations. This is perhaps counterintuitive in the sense that one might assume that in the self-interested market world dominated by the supposed *homo economicus*, individuals who make poor predictions would be certain to be burned. On the other hand, consider the following factors: First, the market provides feedback to individuals regarding their judgment. Since one can see the prices at which shares are trading, one is acutely aware of the extent to which one is an outlier. Second, markets exhibit a central tendency in that they prevent trades based on extremely poorly calibrated judgments from occurring, and/or temper the ill effects of such judgments. Offering to buy (sell) an eventually worthless (worthy) share for a higher (lower) than necessary price would be immediately taken advantage of in a one-on-one trading situation. But since the market mechanism searches for the best possible trade based on other prices quoted by individuals (some of whose predictions would be more reasonably calibrated), such opportunism is mitigated. In other words, one may offer to buy a (eventually) worthless share for a higher than necessary price. However, since the market system searches out all potential trades, it would try to identify individuals willing to sell the share for less (which, by definition, is likely to happen since the quoted price is an outlier in one direction). Thus, a potential social function performed by markets would be to protect constituents who make extremely poor decisions, such as aging adults with impaired decision-making.

Thus, we (1) hypothesize that striatal aging could lead to poor prediction quality (dysregulation in encoding of prediction error), thus impacting decision-making in some older adults; and (2) propose a systemic, market mechanism that could contain and protect aging adults from impaired prediction quality.

2. Materials and Methods

2.1 Summary

We tested this proposition in the context of the 2008 U.S. Presidential race primary cycle, utilizing the IEM. A group of healthy, community dwelling older adults predicted winners of the U.S. Presidential nominations in a repeated measures (January-April 2008), ecologically-valid experiment. The group traded shares (amongst themselves) of political candidates in the primary race, much like commodities on a stock market. Participants had the task of predicting each candidate's chances of winning the party ticket, and these predictions were converted into buying/selling quotes. The performance of the 14 older adults was compared against a simultaneous, open, primary election market administered by the IEM, involving approximately 1000 younger traders.

2.2 Target group

Participants were a group of healthy, community dwelling older adults ($N = 14$; 90% male; > 55 years of age: $M = 74$, $SD = 5.6$ years). These older adults were well educated ($M = 16.6$, $SD = 2.9$ years) and had above-average intelligence (Full Scale IQ as measured on the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999), $M = 121.3$, $SD = 11.9$). Of the 14 older traders, 7 were classified as Impaired decision-makers (6 had structural brain MRI (MRI)) and 7 as Unimpaired decision-makers (5 had MRI), based upon performance on the Iowa Gambling Task (IGT) (Denburg et al., 2005), a validated, complex

decision-making task that reliably classifies decision-making capacity (Bechara, 2007). All 14 had otherwise intact cognitive functioning, as determined by extensive neuropsychological testing.

2.3 Characterization of Impaired vs. Unimpaired decision-makers (target group) based on performance on the Iowa Gambling Task (IGT)

The IGT was designed to mimic real-life decision-making: resembling real-world contingencies that factor reward and punishment (winning and losing money) in such a way so as to create a conflict between an immediate, luring reward and a delayed, probabilistic punishment; and offering choices that may be risky, without obvious explanation of how, when, or what to choose. The IGT involves 100 card selections from each of four decks. Some selections are followed by a reward (financial gain), while others are followed by both a reward and a punishment (financial loss). The task is created in such a way that decks with lower immediate reward have lower long-term punishment, and yield an overall net gain (decks C and D, referred to as “Good” decks); decks with higher immediate reward have higher long-term punishment, and yield an overall net loss (decks A and B, referred to as “Bad” decks). Participants are not informed about the reward/punishment schedules, and the schedules cannot be calculated mathematically. For each participant, we created an overall index of performance, specifically, the sum of good deck selections minus the sum of bad deck selections $[(C + D) - (A + B)]$. Using the rationale that random behaviour on the IGT would yield a score of zero in this formula, we categorized each older adult as Unimpaired or “Impaired,” based on whether the overall performance index differed significantly from zero (using the binomial test), and in which direction (Siegel & Castellan, 1988). Older adults who had indices in the positive direction were categorized as “Unimpaired,” and those who had indices in the negative direction were categorized as Impaired (Denburg et al., 2005). All 14 had otherwise intact cognitive functioning, as determined by extensive neuropsychological testing.

2.4 Structural Magnetic Resonance Imaging (sMRI) for *in vivo* volumetric analysis

Brain MRI was available on 11 of the 14 participants. Of the 14 older participants, 3 could not enter the MRI scanner (2 had pacemakers and 1 was claustrophobic). Thus, three-dimensional (3D) T1 weighted MRI scans were obtained for 11 older participants on a 1.5 Tesla General Electric SIGNA System (GE Medical Systems, Milwaukee, WI), using a spoiled gradient recall sequence with the following parameters: 1.5 mm coronal slices, 40 degree flip angle, 24 msec TR, 5 ms TE, 2 NEX, 26 cm FOV and a 256X192 matrix. Volumes of left (L), right (R), bilateral (Bi) grey and white matter frontal, parietal, occipital, temporal cortices; L, R, Bi cerebellum; L, R, Bi caudate, putamen, thalamus were calculated using BRAINS2 (Brain Research: Analysis of Images, Networks, and Systems 2) software (Magnotta et al., 2002). Regions of interest (ROI) in volumetric analyses for purposes of this study were the left (L), right (R) and bilateral (Bi) caudate, putamen and grey/white matter volumes of L, R and Bi frontal cortex. These were based on robust parcellation schemes provided by the software BRAINS2 (Powell et al., 2008). The ROIs were chosen based on regions known to mediate preferences in social and monetary reward-based probabilistic learning (Behrens, Laurence, & Rushworth, 2009; Delgado, Locke, Stenger & Fiez, 2003). The ROIs were normalized for intracranial volume for all analyses.

2.5 Comparison group

The performance of the 14 older adults was compared against a simultaneous, open, primary election market administered by the IEM, involving approximately 1000 younger traders (90% male; $M = 45.8$, $SD = 14.4$ years of age).

2.6 Task: Trading on the Iowa Electronic Market

Participants were endowed with 10 shares for each candidate and \$10 in the first session and, again, \$10 in the second session in two closed markets (Republican and Democratic primary races of the 2008 U.S. Presidential Elections). Trading occurred in a laboratory on four days over a period of 4 months (January, February, March, and April 2008), using a computer interface. On each day, participants were first trained to use the trading interface, following which they would trade for 1 hour on the Democratic market followed by 1 hour on the Republican market). Participants traded shares of Democratic and Republican candidates as though they were commodities on a stock market. The goal was to maximize one's earnings on this market by accurately predicting the winning candidate. Payouts were made after the Presidential primaries ended in the summer of 2008. The advantages of utilizing election markets include readily available public information (with frequent, accessible news updates), enormous public interest, and a behavior (making election decisions) with which persons are very familiar. This is a relatively easy, highly attractive and topical trading environment for an experimental, aging, novice-trading group and requires less training than in simulated, traditional, stock trading (Berg et al., 2008).

During the course of this study, the participants were repeatedly asked for their election expectation of each candidate – that is, to what extent they thought each candidate was likely to win. This was likened to dividing bingo tokens across the possible scenarios (i.e., the likelihood of each candidate winning). To illustrate, certainty that candidate A will win would entail placing all bingo tokens on that candidate. An equal likelihood that one of two candidates will win (and absolutely no chance that any of the others might) would entail putting an equal amount of bingo tokens on each of those two candidates (to hedge bets). Thus, the expectations the participant generated (which would have to sum to 1) were used to derive buying and selling prices for shares of each candidate

The software then examined the prices quoted by the other participants to determine opportunities to trade. If any had quoted selling (buying) prices lower (higher) than the first participant's values, the software bought (sold) those shares on the first participant's behalf. Thus, all a participant was required to do was to update predictions of the likelihood of each candidate winning the primary.

Participants met once a month to trade shares of the candidates. They could make predictions as often or as rarely as they liked. The feedback after each prediction was an updating of their portfolio (assuming any trades occurred) and an updating of the current market prices for each share. The delay between feedback and the subsequent choice was again up to the individual – they could trade as frequently or rarely – or not at all – as they saw fit. The participant was free to trade (make predictions) as frequently as s/he chose during the one hour of trading (per market), every month. Every time the participant made a prediction, the software would immediately update his trading (viewing) page to reflect the latest market price for each candidate, current share holdings (for each candidate) and trading money available – all of these based on the participant's latest prediction and simultaneous trading of other aging participants in the room (see Figure 1). Contracts for the eventual recipients of the party nominations paid out at \$1, while the remaining shares were worth nothing.

3. Results

A number of analyses were conducted. First, to examine whether Impaired decision-makers did in fact make worse IEM predictions, we needed to identify a standard of comparison. Since the IEM market has been demonstrated to show a 'crystal ball' quality of better accuracy than polls (Berg et al., 2008), the share price predictions of the main IEM

consisting of mainly younger traders was taken as a standard of comparison and each individual's share price predictions (in the experimental group) were compared against this standard. Then, to examine the market protection hypothesis, any instance of the actual trading price differing from the "willing to pay/accept" (WTP/WTa) prices was coded as an instance of market protection. For example, if one was able to buy a share for less than what one was willing to pay for it, or sell a share for more than the minimum amount one wanted for it, such instances were coded as cases of market protection – that is, the market served the participant better than his/her own predictions did. On each of these instances, we also calculated the amount of money that was saved for a trader by the market mechanism. We were thus able to examine the frequency of protection – how often one was protected by the market – as well as the magnitude of protection – how much money was saved for a trader by the market.

3.1 Prediction Quality

Given the 'crystal ball' quality ascribed to the main IEM, the following procedure was adopted to examine the quality of older adult predictions. The trading prices for each candidate by each older adult on each trading day was compared to the final trading price on the main IEM for each candidate on the same day. A squared difference score was calculated as a measure of the error (i.e., how different older adult final trading prices were from the main IEM's trading prices). Thus in this study, prediction error is defined as the difference between an actual outcome and its prediction (with the main IEM price serving as the proxy for the former), in principle, aligned with the prediction-error theory of dopamine (Schultz, Dayan and Montague, 1997). However, this study records a behavioural measure of prediction error, and while the research assumes that striatal aging may impact magnitude of prediction error, there is no direct evidence of dopaminergic encoding of prediction error in a structural imaging study. Hence no conclusions surrounding neuronal encoding of prediction error are drawn. Additionally, in utilizing a squared difference behavioural score of prediction error, this study does not examine valence of prediction error, but merely its magnitude and frequency of occurrence.

Group comparisons yielded a significant main effect for group (Impaired vs. Unimpaired), $F(1, 294) = 6.61, p < .01$, Cohen's $d = 0.31, r = 0.15, p_{rep} = 0.97$. As shown in Figure 2a, the Unimpaired older adults had significantly smaller errors compared to the Impaired older adults.

Errors of the Impaired and Unimpaired older adults were compared by examining errors across all candidates on the four trading days (Figure 3). The 7 Unimpaired decision-makers were closer to the comparison group of younger traders in accurately predicting the winning nominees, and thus had similar share prices, and significantly outperformed the 7 Impaired decision-makers.

The graphs above illustrate the share prices quoted by the two groups of older traders compared to the group of younger traders on the main IEM. Aggregated across all candidates, a main effect emerges with the unimpaired older adults being significantly closer to the younger traders compared to the impaired older adults.

Prediction accuracy was substantiated by a neural substrate, i.e., regression analyses revealed that lower caudate (bilateral) volume was associated with larger prediction errors (Figure 2b), $F(1, 236) = 20.9, p < .0001$, Cohen's $d = 0.59, r = 0.29, p_{rep} = 0.99$.

3.2 Market Protection

The second central hypothesis of this study is that the market serves to protect impaired decision-makers who make poor predictions. The reason for this is the fact that the market

does not allow wildly miscalibrated predictions to attain fruition and tempers these errors. If an individual were to quote a higher (lower) than necessary buying (selling) price for a share, the market would search all other quoted prices before executing a trade. Thus, the market would likely find more reasonable trading prices for this person – that is, they would buy (sell) their share for lower (higher) than their quoted price. Any trade that resulted in a difference between the quoted price and the actual trading price was thus coded as an instance of market protection. The market protection itself was examined at two levels – frequency and magnitude. Frequency refers to the number of times an individual made a poor prediction where the market protected the individual. Magnitude refers to the extent of protection – that is, conditional on a poor prediction, how much money was saved for the individual by the market (as compared to a one-on-one trading situation where the opposite party could capitalize on the individual's poor predictions). Thus, individuals who consistently make poor predictions would be substantially worse off in one-on-one negotiations where their poorly calibrated judgments would leave them vulnerable to exploitation.

Note that this is not a function of the way the market clearing is set up. An instance of market protection is not equivalent to putting in a limit order as opposed to a market order. A market order is an order to buy or sell shares at the market price, while a limit order sets a price at which one would like to buy or sell shares. A market order would be more likely to result in a trade (provided willing buyers/sellers can be found) at the risk of paying a higher price than needed. According to this argument, individuals may put in limit orders for other reasons, such as saving on trading time, knowing that this would protect them. It should be pointed out that in our study, participants are not directly quoting prices or placing orders but are entering their expectations about each candidate's chances and their orders are imputed from those expectations. Further, note that this is a strategy that could be employed by the impaired as well as the unimpaired participants and would not provide an explanation for any observed differences – that is, even assuming that individuals strategize in such terms, this strategizing is open to all individuals and would not explain why impaired individuals are protected to a greater degree. If the argument is weakened to say that impaired participants may strategize poorly and pursue inappropriate goals (and thereby incur unexpected slippage) that is precisely what the 'protection against oneself' idea is attempting to capture.

The market protected the Impaired older adults on more occasions than it did the Unimpaired (Figure 4a), Wald chi-square = 11.6, $p < .001$, $\Phi = 0.9$, odds-ratio = 1.3, $p_{rep} = .99$. Note that the Unimpaired earn more money in the market since earnings are tied to their overall higher prediction accuracy. However there were more instances of huge predictions errors when the Impaired bid higher than necessary or tried to sell shares at too low a price, and the market protected participants from these errors by preventing poor trades from going through and/or finding more profitable prices. If these individuals made similar errors in situations of one on one negotiation they could incur huge losses and be taken advantage of.

We also examined market protection as a function of caudate volume. Logistic analyses revealed that the market actually insulated those with reduced caudate volume, on more occasions, from the consequences of poor prediction. Further, regression analyses revealed that the amount of money saved for individuals by the market mechanism was greater for those with reduced caudate volume. That is, individuals with lower caudate volume displayed a greater number of instances when they required market protection to shield them from their own poor judgments (Wald chi-square = 8.65, $p < .003$, $\Phi = 0.89$, $p_{rep} = .98$), and conditional on market protection, these individuals were saved a larger amount of money on any protected trade, $F(1, 10) = 4.2$, $p < .07$, $p_{rep} = 0.9$. Thus, the market protected

those with reduced caudate volume more frequently (Figure 4b), and on those occasions tended to save them more money (Figure 4c), than it did those with higher caudate volume.

4. Discussion

In summary, our data suggest that some older adults suffer prediction deficits that appear to have an underlying neural correlate, namely, reduced caudate volume. The market mechanism may serve to protect these impaired decision-makers.

4.1 Striatal aging

Within the striatum, the caudate in particular is important to distinguish between magnitude of reward and punishment (Delgado et al., 2003) and anticipatory (Samanez-Larkin et al., 2007) and outcome processing (Cox et al., 2008) facilitating prediction accuracy and choice of future direction. Thus, by integrating values of differing valence and magnitude, the caudate may help create a “social evaluatory signal” (Hsu, Anen & Quartz, 2008) in response to reward-based social and financial cues.

Regional changes in brain volume in healthy adults indicate that the dorsal striatum undergoes substantial shrinkage with age (Raz et al., 2005a; Raz, 2005b; Walhovd et al., forthcoming). However, the literature is equivocal on whether these changes are linear or non-linear; and with regards to which structures within the striatum are best preserved or degenerate the most with age. We believe that our study can shed some light on this, especially on the functional changes that may accompany striatal aging. Longitudinal studies (Raz et al., 2005a; Raz, 2005b) indicate that volumetric reduction of the dorsal striatum is linear and unrelated with age (rate of shrinkage in young adults is approximately the same as in older adults). One longitudinal study (Raz et al., 2005a) indicates that the maximum rate of volumetric reduction (every 5 years) is the highest for the caudate nucleus ($d = 1.06$) compared to other brain structures, except the cerebellum ($d = 1.07$). Another longitudinal study indicates that the caudate ($1.2 SD$) shrinks at a higher rate than the putamen ($0.85 SD$) every five years (Raz, 2005b). By this calculation, when an individual reaches old age, the caudate would have undergone substantial shrinkage compared to when the individual was a young adult. Individual differences in caudate volume amongst older adults could perhaps be partially accounted for by a higher rate of shrinkage in some adults. This could explain the correlation of caudate volume with prediction accuracy in older adults where the market especially protects those with reduced caudate volume (higher prediction error) (Figure 2).

In comparison to the caudate, the putamen shrinks at a slower rate (Raz, 2005b) and has been associated with the stimulus-action-reward association of habitual learning (Haruno & Kawato, 2006), unlike the caudate that is responsive to novel contingencies (Yin & Knowlton, 2006). However, a recent cross-sectional study (Walhovd et al., forthcoming) of volumetric decline associated with healthy aging indicates significant non-linear, heterogeneous decline of dorsal striatal structures, with putamen volumetric reduction being relatively severe in comparison to the caudate. The caudate appears to be the best preserved of all striatal structures in old age, as per this study. In our study however, the extent of prediction error was not predicted by volume of the putamen ($F(1, 10) = 1.71, p > .2$), nor the magnitude of market protection ($F(1, 10) = 2.58, p = .15$).

Prediction error in complex decision-making extends to the prefrontal and cingulate cortex (Behrens et al., 2009; D’Acemont et al., 2009), but neither the extent of prediction error nor market protection was predicted by frontal grey or white matter volume (F ’s < 1) in our study.

Other than significant volumetric decrease of the caudate nucleus across the lifespan, loss of dopaminergic biomarkers in the striatum of up to 10% per decade from early to late adulthood, may account for poor strategic performance amongst older adults, especially in complex decision-making (Haruno & Kawato, 2006; Raz et al., 2005a; Raz, 2005b).

This study has several limitations. While the study was widely advertised, a very small group of participants actually signed up (self selected to be mostly males) to participate in the trading environment. This was in spite of offering various financial incentives: reimbursement for time spent on the task over 4 months, real money to trade with, as well as monetary pay-outs for stocks held and profits accrued at the end of the trading period. Poor enrollment may have been due to the long-term (4 month) commitment that was required of participants and reticence (especially amongst aging females) around perceived numeracy complexities involved in trading on the stock market (although participants were retrained before every trading block and were merely asked to list candidates' likelihood of winning the nomination). Thus, while prior experience on the stock market may have influenced enrollment, it is unlikely to have influenced task performance, since all the participant was asked to do was update his/her perception of a candidate's likelihood of winning the nomination (at every trading instance), while the trading software converted this perception into trading bids. It is difficult to argue demand characteristics in the data, since the participants were asked to make political predictions and were blind to our market-related hypotheses. Secondly, their explicit instructions were to update these predictions in a trading environment, in order to maximize monetary gain. Thus self-interest was on the line in this performance task, and we were not using subjective rating scales (conditions that may be most susceptible to demand characteristics). Hence, it would be near impossible for participants to second guess our hypotheses or behave in a way that would refute or support them.

Our analyses and findings are preliminary, particularly given the small sample size. That said, our limited sample size is partially offset by the repeated measures design where we have utilized a number of trading instances/observations per individual (approximately 900 orders per individual) across 4 months of trading. This study also lacks a true control group. However, we invoked a normative standard, the main IEM open, trading market (comprised of mainly younger individuals), which operated simultaneously as our closed, aging market. Since the IEM has historically achieved higher prediction accuracy in elections than polls (Berg et al., 2008), we calibrated aging prediction error against this open market, in lieu of a control group. While it would have been ideal to have a control condition that tracked prediction error (without a market mechanism), the IGT serves as a stable indicator of individual judgment and decision-making ability (Denburg et al., 2005; Waters, Xiao, Denburg, Hernandez & Bechara, under review), as is observed in this case through the correlations between prediction error and IGT performance (Figure 2). However, one limitation with the IGT is that in its attempt to successfully mimic real-life decision-making, the task becomes sufficiently complex that it is hard to experimentally delineate and define the decision-making processes involved. The IGT has also been shown to have reliability issues in the literature (Buelow & Suhr, 2009). Mood, temperament and personality may have played a minor role in prediction and decision-making quality in this study, since the literature has shown that IGT performance is negatively impacted by high Reward Responsiveness and Fun- Seeking personality traits, high behavioural activation (accompanied by poor behavioural inhibition) and negative mood (Buelow & Suhr, 2009); also correlation between neuroticism and poor decision-making in older adults is known to exist (Denburg et al., 2009).

Although behavioural and psychophysiological studies have pointed to age related decision-making decline (D'Acremont et al., 2009; Denburg et al., 2006; Korniotis & Kumar, 2011)

and fMRI and PET (Fein et al., 2007; Rieckmann & Backmann, 2009; Samanez-Larkin, Kuhnen, Yoo & Knutson, 2010; Yin & Knowlton, 2006) studies have documented dopaminergic noise or striatal changes in cognitive aging, this study is one of the first to correlate impaired decision-making and *magnitude* of prediction error to reduced *in vivo* volume of the caudate, in an older population. In the case of aging, it is possible that older adults making larger prediction errors are perhaps experiencing dysfunction in parametric neuronal encoding of those errors, related to striatal (caudate volume and dopaminergic) decline. We also suggest that aggregate level market dynamics may offer a novel, social, systemic, scaffolding mechanism to protect against age-related cognitive decline. This could be an important means of supplementing more individually oriented efforts such as physical/mental exercise or diet (Van Praag, 2009).

4.2 Implications

Everything we do monetarily involves some form of trade. Social scaffolding, if offered by markets, has implications for senior citizens, where perhaps markets could be arranged to protect poor decision-makers with implications for public policy and life skills for the elderly. The findings from this research study could also extend to poor decision-makers beyond the elderly. Thus, hedge funds and bonds if converted into organized exchanges for trading could better protect vulnerable decision-makers. The provision of medical advocacy in a form that promotes collective medical decision-making amongst patients and their caregivers may benefit poor decision-makers, not just the elderly. Pooled insurance plans (to reduce the stress of choice overload) or neighbourhood groups (to promote social scaffolding) might be some ways to reduce decision-making vulnerability in settings of one-on-one negotiation by supporting their dealings with a market mechanism.

Markets themselves have been known to collapse. While these are some possible ideas by which the market mechanism may assist poor decision-makers, further research is necessary to establish and delineate the boundaries of such protection, especially in terms of the conditions and the populations that would benefit from such a mechanism. This study is one example emerging from behavioural decision-theory, that indicates the existence of cognitive bias amongst human decision-makers; especially that decision-making, contrasted against economic rational choice, is constrained by neuropsychological processes and an underlying neural substrate (Smith, 2001), subject to organic vulnerabilities such as aging. Thus, market-based protection in a collective, collaborative decision-making setup, may occur in the form of the market vetoing excessive risk-taking (Rockenbach, Sadrieh, & Mathauschek, 2007) or grossly erroneous predictions made by a single individual, thus limiting his losses, as has been the case in our dataset. Note that good decision-makers made more money in this study, while the poor decision-makers were constrained in their losses, since the market created a trading boundary that did not allow extremely poor predictions to result in financial transactions, thus protecting poor decision-makers from themselves. While the market mechanism itself may be a better protection for vulnerable decision-makers than one-on-one negotiations, improved market and investor protection regulation that takes into account these neuropsychological vulnerabilities and inherent cognitive biases, could enhance protection offered by the market mechanism (Avgouleas, 2006). If impaired decision-makers amongst the elderly could piggyback on the smart decision-makers through a market mechanism, then they could be materially better off without compromising their quality of life or independence.

This study is an example of the existence of non-obvious and counter-intuitive cross-level interactions between macro socio-economic systems and the brain. Neuro-economics thus far, has largely been confined to exploring the influence of individual agency on emergent, economic phenomena (Schultz, 2009). In contrast, this neuroscientific study, in an ecologically valid, top-down approach, attempts to translate how large scale socio-economic

phenomena such as market forces may also serve and protect the vulnerable brain. Thus the market mechanism has the potential to serve as novel, systemic, socio-economic aging intervention.

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Candidate	Current / Last Holdings (shares)	Market Price	Your Prediction (%)	Prices from Prediction (Buy / Sell) ?
Hillary Clinton	3	.38	<input type="text" value="30"/>	\$0.29 / \$0.31
John Edwards	0	.01	<input type="text" value="0"/>	
Barack Obama	12	.61	<input type="text" value="70"/>	\$0.69 / \$0.71
Other Candidate			<input type="text" value="0"/>	
			Total = 100	
Cash Balance:	\$7.52		<input type="button" value="Submit Trade"/>	

Figure 1.
Computer trading interface.

Fig.2.

Decision-making Impaired vs. Unimpaired: Prices quoted by the Unimpaired older adults paralleled prices in the main IEM market (consisting of mostly younger traders) to a closer degree, as compared to the Impaired older adults, evidenced by smaller prediction errors (Fig.2 a.), where errors were coded as the difference between the quoted price and the price on the main IEM market. Prediction accuracy was substantiated by a neural substrate: lower caudate volume was associated with larger prediction errors $F(1, 10) = 8.36, p = 0.02$ (Fig 2b), and the lower the caudate volume, the greater the probability of market protection (Wald chi-square = 8.65, $p = .003$.)

Figure 3.

Figures 3.a and 3.b provide prices quoted by the 3 categories of traders for shares of Obama and McCain, who eventually won the nominations for the Democratic and Republican parties, respectively. Figures 3.c and 3.d provide prices quoted for the other contenders for the Democratic nomination. Figures 3.e and 3.f provide prices quoted for the other contenders for the Republican nomination.

Figure 4.

The market insulated the 7 Impaired decision-makers from the consequences of poor prediction (Fig. 4a), as poor predictions [offering to sell (buy) shares for lower (higher) than necessary prices] were not penalized as heavily as they might otherwise have been. A logistic regression yielded a significant main effect for categorization of decision-making ability (Wald chi-square = 11.55, $p = .001$), as Impaired decision-makers were more likely to make poor predictions and consequently be protected by the market. The lower the caudate volume, the greater the probability of market protection (Wald chi-square = 8.65, $p = .003$ (Fig. 4b). Lastly, conditional on market protection, caudate volume was associated with the amount of money saved (Fig. 4c), $F(1, 10) = 4.17$, $p = .07$, as the lower the caudate volume, the more money saved by the market protection mechanism. In short, lower caudate volume was associated with larger and more frequent prediction errors, leading to greater likelihood of market protection.