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**Event-Related Potentials Reveal  
Differential Brain Regions Implicated  
in Discounting in Two Tasks**

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## **Abstract**

The way people make decisions about future benefits – termed *discounting* - has important implications for both financial planning and health behaviour. Several theories assume that, when delaying gratification, the lower weight given to future benefits (the discount rate) declines exponentially. However there is considerable evidence that it declines hyperbolically with the rate of discount being proportionate to the delay distance. There is relatively little evidence as to whether neural areas mediating time-dependent discounting processes differ according to the nature of the task. The present study investigates the potential neurological mechanisms underpinning domain-specific discounting processes. We present high-density event-related potentials (ERPs) data from a task in which participants were asked to make decisions about financial rewards or their health over short and long time-horizons. Participants (n=17) made a button-press response to their preference for an immediate or delayed gain (in the case of finance) or loss (in the case of health), with the discrepancy in the size of benefits/losses varying between alternatives. Waveform components elicited during the task were similar for both domains and included posterior N1, frontal P2 and posterior P3 components. We provide source dipole evidence that differential brain activation does occur across domains with results suggesting the possible involvement of the right cingulate gyrus and left claustrum for the health domain and the left medial and right superior frontal gyri for the finance domain. However, little evidence for differential activation across time horizons is found.

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## **Introduction**

Economics has increasingly attempted to provide empirical micro-foundations based on psychology and neuroscience and this has led to a flourishing body of interdisciplinary work (e.g. 1,2,3,4). One area of scientific investigation in this emerging discipline of neuroeconomics is the area of temporal discounting. Substantial research has shown that when people are faced with intertemporal choices, a clear tendency exists for discount rates to be proportionate to delay, termed hyperbolic discounting (5,6). Hyperbolic discounting has been utilised to explain a range of phenomena in the behavioural economics literature, particularly in the area of procrastination (7,8).

One idea proposed to explain hyperbolic discounting is that when humans are presented with a choice between a smaller, sooner reward and a larger, later one a conflict arises between emotion (favouring immediate gratification) and rationality (favouring rewards that will be more beneficial in the long-run; 3,9,10,11). This dual systems theory is supported by a number of studies in the field of neuroeconomics, which postulate that the limbic system drives preferences for immediate or short term rewards whereas preferences for long term rewards are mediated by parts of the prefrontal cortex and associated areas (12,13).

Recently, McClure et al. (12) conducted the first functional Magnetic Resonance Imaging (fMRI) study to investigate the neural correlates of time discounting and found that while parts of the lateral prefrontal cortex and posterior parietal cortex ( $\delta$  areas) are engaged consistently by intertemporal choices regardless of delay, parts of the limbic structures associated with the dopamine system, including paralimbic cortex ( $\beta$  areas), are preferentially activated by decisions involving immediate rewards, supporting Laibson's (6) dual-self  $\beta$ - $\delta$  model at a neurobiological level. In particular, areas active when

immediate rewards were selected included the ventral striatum, medial orbitofrontal and medial prefrontal cortex, as well as posterior cingulate cortex and left posterior hippocampus, whereas all intertemporal choices activated left and right intraparietal cortices, right dorsolateral prefrontal, right ventrolateral prefrontal, right lateral orbitofrontal cortex, as well as motor and visual cortex. The authors found that subjects chose longer term options where greater relative fronto-parietal activity was observed, and conclude that choosing between immediate and delayed gratification constitutes a battle between limbic structures that activate for current rewards and newer cortical regions that evaluate trade-offs.

McClure et al. (13) extended their 2004 findings to primary rewards (fruit juice and water) and time delays of minutes instead of weeks. McClure et al. (13) state that their subjects' behavioural choices are described by a two-system discounting model and that analysis of the brain-imaging data also identified two different neural systems which appeared to be associated with each of the two discounting systems. Consistent with their 2004 findings, limbic activation was greater for choices between an immediate and a delayed reward than for choices between two delayed rewards. Lateral prefrontal cortex and posterior parietal cortex responded similarly whether choices were between an immediate and a delayed reward or between two delayed rewards. Discount functions were fit to the identified  $\beta$  and  $\delta$  brain areas and these discount functions corresponded well for the  $\delta$  system but not for the  $\beta$  system.

Monterosso, Ainslie, Xu, Cordova, Domier and London (14) carried out an experiment to investigate the neural basis of delay discounting in methamphetamine abusers and controls. Task effects were comparable to McClure et al. (12) as the pattern of task-related signal change observed by Monterosso et al. (14) strongly resembled the frontoparietal network observed by McClure et al. (12); however, unlike McClure et al.

(12), Monterosso et al. (14) did not observe activity in limbic / paralimbic regions. The authors hypothesize that this inconsistency among the two studies may be due to the reliance on hypothetical rewards in their study.

Wittmann, Leland and Paulus (15) found that strong activation in the bilateral posterior insular cortex was associated with the selection of delayed reward (as well as activity in left posterior cingulate, superior temporal and angular gyri, inferior parietal lobule and cuneus). Greater activation in the striatum was associated with the presentation of options where delays were shorter than one year versus delays longer than one year, which gives support to the work of McClure et al. (12,13) who found that the ventral striatum was active when immediate rewards were selected, however their task involved a maximum time delay of 6 weeks to the delayed reward. Other studies have implicated immediate rewards with activations of lateral orbitofrontal cortex and striatum, while future rewards activated dorsolateral prefrontal and inferior parietal cortices (16), with suggestions that the prefrontal cortex may predict choice behaviour while the insula responds to changes in reward magnitude (17).

This paper addresses the question of whether the discounting patterns and their neurological substrates vary depending on the nature of the discounting task, in particular if the same time preferences apply to different domains such as finance, health, education etc. Research indicates that discounting is in fact domain specific, with both rates of trade and decision processes differing across the domain of the decision. Chapman and Elstein (18) examined two domains (money and health) and found that although these domains showed both a delay and magnitude effect, they also found what they called *domain independence*, i.e. that decision makers do not conform to discounted utility theory but instead use different discount rates for different domains. In a series of experiments Chapman (19) demonstrated that health and money decisions are similar in that they both

demonstrate the delay, magnitude and sign effects; however decision makers use unrelated temporal discount rates for health and money. In a review of health discounting literature, Chapman (20) states that there is little correlation between discount rates for health and money, and this indicates that individual decision makers do not use the same rate for these two domains. Petry (21) evaluated the manner in which outcomes are devalued over time in drug abusers and non-substance abusing controls. Three domains were tested: money, health and freedom. Hyperbolic discounting functions best described the data. Drug abusers discounted all types of delayed outcomes at higher rates than controls. Money was discounted more rapidly than freedom, which was discounted more rapidly than health.

In the present study, a task was designed to explore the electrophysiological underpinnings of temporal discounting. High-density ERPs were employed to investigate the neurological mechanisms underlying domain specific discounting processes in two domains, finance and health. Participants were required to make decisions about financial rewards or their health at present (where participants must decide now; ‘present condition’) and future (where they must hypothetically decide at 50 years of age; ‘future condition’) time-horizons, indicating a preference for either immediate (‘immediate response’) or delayed (‘delayed response’) hypothetical rewards within each condition. While ERPs do not share the same spatial resolution as fMRI, the temporal resolution of ERPs is far superior to blood flow measures and the time course of processing in the cortex can be seen with millisecond accuracy. Also, source localisation software allows the cortical generators of scalp recorded potentials to be reliably determined.

This paper is, to our knowledge, the first to examine potential neurological mechanisms underpinning *domain-specific* discounting processes at different onset intervals, and the behavioural and neurocognitive operations involved in this form of

decision making. The study firstly reexamines Chapman's (18,19,20) behavioural results on discounting, which suggest little correlation between discounting rates and processes across different domains. Following from this, a key question is whether discounting in different domains is mediated by different brain processes. A corollary of this is whether the hyperbolic discounting generally observed for financial trade-offs apply in the same way when health trade-offs are considered.

## **Results**

### ***Behavioural Data***

Mean frequency of responses and reaction times for each domain (finance and health) for 'present condition immediate response' and 'present condition delayed response' and 'future condition immediate response' and 'future condition delayed response' are illustrated in Figure 1 A and B, respectively. A repeated-measures ANOVA was carried out on response frequencies and reaction times in each category to test for significant interactions.

Participants responded somewhat more frequently to the 'present condition delayed response' and 'future condition delayed response' options in the financial domain and showed a strong preference for immediate rewards for both 'present condition' and 'future condition' in the health domain. For response frequencies a significant main effect was observed for immediate/delay [ $F(1, 16)=21.526, p=0.000$ ] and a significant interaction was observed for domain X immediate/delay [ $F(1, 16)=91.282, p=0.000$ ]. For reaction times a significant main effect was observed for domain [ $F(1, 16)=14.608, p=0.002$ ] and a significant interaction was observed for domain X immediate/delay [ $F(1, 16)=18.752, p=0.001$ ].

Results for regression analysis of financial discounting and health discounting are presented in Table 1. Mean discounting rates were as follows; 'finance present condition'

(mean=0.0729, SE=0.0082), 'finance future condition' (mean=0.0830, SE=0.0090), 'health present condition' (mean=0.0649, SE=0.0239) and 'health future condition' (mean=0.0842, SE= 0.0289). The behavioural results reveal strong effects of the magnitude of the reward differences with respondents being increasingly likely to delay as the rewards for doing so increased. However, we do not find evidence in either health or finance that respondents delay rewards hyperbolically in the sense that neither immediate health nor finance are valued less in the future and indeed seem to be valued more with respondents being more likely to delay health losses in the future condition and less likely to delay finance gains.

### ***Event-Related Potentials Data***

When the ERP data were collapsed for 'finance overall', 'health overall', 'finance present condition', 'finance future condition', 'health present condition' and 'health future condition', three main components were observed in all conditions. The components observed were a posterior N1 (peak at 160ms at Pz), a frontal P2 (peak at 190ms at FCz) and a posterior P3 (peak at 300ms at P4) with further positivity at central electrode sites peaking at approximately 360ms at CPz. The ERP waveforms for 'finance overall' and 'health overall' for the following electrode sites, Pz, FCz and P4 are displayed in Figure 2 along with corresponding scalp topographies for each component.

A repeated-measures ANOVA was carried out for each of the three main components (N1, P2 and P3) to test for significant differences. For the N1 component a significant main effect was observed for domain [ $F(1, 16)=10.989, p=0.004$ ] and immediate/delay [ $F(1, 16)=10.769, p=0.005$ ] and a significant interaction was observed for domain X immediate/delay [ $F(1, 16)=23.309, p=0.000$ ] and for domain X size X immediate/delay [ $F(1, 16)=6.533, p=0.021$ ]. In a comparison across domains, paired



samples t-tests were used to test the statistical significance of the differences in mean AUC for finance now-health now and finance 50-health 50. These t-tests found significance for N1 ('present condition':  $t(16)=2.714, p=0.015$ ; 'future condition':  $t(16)=3.238, p=0.005$ ).

For the P2 component a significant main effect was observed for domain [ $F(1, 16)=4.869, p=0.042$ ], size [ $F(1, 16)=9.353, p=0.008$ ] and immediate/delay [ $F(1, 16)=6.618, p=0.020$ ] and significant interactions were observed for domain X 10/15 years [ $F(1, 16)=16.039, p=0.001$ ], domain X 10/15 years X size [ $F(1, 16)=4.893, p=0.042$ ], domain X immediate/delay [ $F(1, 16)=21.627, p=0.000$ ], domain X 10/15 years X immediate/delay [ $F(1, 16)=5.334, p=0.035$ ] and domain X size X immediate/delay [ $F(1, 16)=9.240, p=0.008$ ]. Paired samples t-tests found significant differences in mean AUC for finance now-health now for P2 ('present condition':  $t(16)=2.471, p=0.025$ ).

For the P3 component a significant main effect was observed for domain [ $F(1, 16)=13.201, p=0.002$ ], size [ $F(1, 16)=13.732, p=0.002$ ] and immediate/delay [ $F(1, 16)=9.120, p=0.008$ ] and significant interactions were observed for domain X 10/15 years [ $F(1, 16)=7.444, p=0.015$ ], domain X immediate/delay [ $F(1, 16)=19.430, p=0.000$ ] and domain X size X immediate/delay [ $F(1, 16)=20.678, p=0.000$ ]. Paired samples t-test found significant differences in mean AUC for P3 ('present condition':  $t(16)=2.644, p=0.018$ ; 'future condition':  $t(16)=3.506, p=0.003$ ).

### ***Dipole Source Analysis***

Dipoles were fitted in a step-wise fashion to account for the three major deflections, the posterior N1, frontal P2 and posterior P3. Comparable dipoles solutions were observed for the N1 and P3 components. Table 2 provides a full summary of the source localization results for N1 epoch (140-180ms) and P3 epoch (280-320ms) for each

condition. However, differences were observed in the source localization results for the frontal P2 interval (170-210ms) (see Figure 3 for MRIs showing dipole solutions for posterior P2 (170-210ms) for ‘finance overall’ and ‘health overall’ and waveforms and MRIs for posterior P2 for ‘finance present condition’ and ‘finance future condition’ and ‘health present condition’ and ‘health future condition’).

#### *Finance Overall*

When the ERP data were collapsed across all conditions for the financial task, sources at visual processing areas as well as right middle temporal and medial frontal areas were associated with financial decisions overall, with right posterior cingulate also implicated. Source modeling resulted in a four dipole solution for the P2 epoch (170 - 210ms), which produced a goodness-of-fit value of 95% (R.V. = 4.632%). Sources include the right posterior cingulate (BA 23), the right temporal lobe (BA 21), the right superior frontal gyrus (BA 8) and the left parietal lobe (BA 7).

#### *Health Overall*

When all conditions for the health task were collapsed a four dipole solution was modelled for the P2 interval (170 – 210ms) giving a goodness-of-fit value of 96% (R.V. = 3.492%). Sources were found near the left parietal lobe (BA 39), the right middle temporal gyrus (BA 39), the right cingulate gyrus (BA 32) and the left thalamus.

#### *Finance Present Condition and Finance Future Condition*

Further source analysis investigations were carried out on the finance data after separating the ‘finance present condition’ and ‘finance future condition’ waveforms. Dipoles were fitted to account for the same three major components (see Table 3 for

source localization results for the N1 and P3 components). For 'finance present condition' for the P2 epoch (170-210ms), a three dipole solution with an R.V. of 11.732% was obtained. Possible cortical generators include the right cingulate (BA 31), the left occipital lobe/cuneus (BA 7) and the right superior frontal gyrus (BA 8). For the P2 epoch, in the 'finance future condition' condition, a four dipole solution (R.V. =4.483%) was obtained revealing cortical generators which include the right posterior cingulate (BA 23), the right superior temporal (BA 22) and right superior frontal gyri (BA 8) and the left parietal lobe (BA 7).

#### *Health Present Condition and Health Future Condition*

Further source analyses were carried out on the health data after separating the 'health present condition' and 'health future condition' waveforms. Dipoles were fitted to account for the same three major components (see Table 3 for source localization results for the N1 and P3 components). For 'health present condition' a three dipole solution was obtained for the P2 epoch (170-210ms). This source model had an R.V. of 7.65% and possible cortical generators include the left and right occipital lobe/cuneus (BA 19/30) and the right medial frontal gyrus (BA 6). For the P2 epoch (170-210ms), for the 'health future condition' a four dipole model with an R.V. of 3.975% was obtained with possible cortical generators which included the bilateral parietal lobe (BA 19), the right cingulate gyrus (BA 32) and the left claustrum.

## **Discussion**

The present study investigated the electrophysiological markers of discounting across two domains, finance and health using a task in which participants were asked to make choices in both domains at present (i.e. decide now) and future (i.e. decide at 50 years of age) time-horizons, indicating a preference for either immediate or delayed hypothetical rewards within each condition..

The results indicate substantial differences in brain areas associated with discounting in discounting tasks across two domains with limbic areas, known to be associated with instinctual feelings and emotions (22,23,24,25,26) and frontal areas, known to be associated with higher order functions such as planning and cognitive control (27,28,29) being differentially activated in health and finance respectively. This is consistent with the idea that health decisions may be more impulse driven, in particular driven by brain areas associated with disgust, with finance decisions being more mediated by prefrontal areas associated with calculation. This is important for dual-systems models of discounting as impulsivity may be differently manifested in different domains depending on the characteristics of the domain. Future work is needed to give a fuller characterisation of the nature of domain specificity in discounting across a number of domains.

The methodology employed allows us also to examine in detail the stages of processing in discounting tasks. Three components were observed for decision making in all conditions. The first component (N1) is common to both health and finance discounting and is likely to be associated with early stimulus evaluation processes in visual areas. The second component (P2) is associated with domain differences in

underlying cortical generators. In particular, P2 is associated with frontal generators responsible for finance decision making and limbic centres responsible for health decision making. The results suggest that this is the most likely neural basis for domain differences in discounting and is likely generated by differences in how the brain evaluates alternatives in the different tasks. Component P3 is common to both health and finance discounting and is associated primarily with frontal and temporal regions and is likely to reflect a decision resolution process common to both tasks. In all components, we observed greater magnitudes in finance than health, which is likely to indicate deeper processing in the finance task than the health task.

We find less evidence for differences in activation dependent on the time horizon of decisions. For the finance domain, there is some evidence of cortical generators in the right superior temporal gyrus for the ‘future condition’ but not for the ‘present condition’. For the health domain, we find additional cortical sources near the left claustrum/insula for the ‘future condition’ but not for the ‘present condition’. Once again, these occur during the P2 latency window which is implicated in domain discounting though the functional significance of these areas in these tasks is unclear. Just as the P2 component may reflect evaluation in domain specific cortical areas, thinking about future consequences within each domain may also recruit unique brain areas.

In summary, the present study builds upon the existing literature in an attempt to reveal domain differences for discounting. The present study also extended the time scales involved in such experiments to reflect real life economic decisions. In conclusion, we provide further powerful evidence that discounting processes are domain specific.\* It

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\* Experiments such as the one outlined in the present study have been criticised due to the use of hypothetical rather than real rewards. In a paper summarising the results of 74 studies, Camerer and

is also the first paper to test for a possible neural basis for such domain specificity and we illustrate differential brain activation does occur across domains with frontal areas implicated in financial decisions and limbic areas involved in health decisions.

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Hogarth (30) examined the effects of financial incentives in experiments. The authors state that in the types of tasks that economists are interested in (they use the examples of bargaining in games and choosing among risky gambles), **the use of financial incentives does not alter behaviour substantially** and the most common finding is that incentives did not affect mean performance. Johnson and Bickel (31) compared discounting of hypothetical and real monetary rewards and found no differences in discounting rates whether the rewards were real or hypothetical.

## **Materials and method**

### ***Participants***

18 volunteers participated in this experiment. After initial data screening, 1 participants' data was removed from ERP analysis due to excessive EEG/EOG artifacts. Of the 17 remaining participants, age range 18 to 29 years (mean 23.65 years), 8 were male and 3 were left-handed. Participants were recruited ad hoc. 16 participants were recruited from the student populations of the National University of Ireland (NUI Maynooth) and the Geary Institute (University College Dublin). 1 participant was in full time employment elsewhere. All participants were in good health, had normal or corrected-to-normal vision and were naïve to the purpose of the study. Participation in the study was on a voluntary basis and participants were not paid for taking part in the study. Informed consent was obtained from all participants. The experiment was conducted in accordance with the Code of Ethics of the World Medical Association, the Declaration of Helsinki and the ethical standards of the APA and approved by the NUI, Maynooth University Ethics Board.

### ***Stimuli***

All stimuli were presented using E-Prime© on an Intel Pentium 4 processor (3.00GHz CPU) and displayed on an LCD monitor. All stimuli were prepared using Adobe Photoshop™ and consisted of two boxes which displayed the two options available to the participant. Stimuli were presented as black writing on a plain white background. Pairs of stimuli were presented and participants made a button press response to indicate which choice they preferred. Stimuli remained on screen until a response was made by the participant. A fixation cross appeared on screen for 1000ms between each trial. For the

financial block the immediate reward was always presented on the left hand side of the screen and the delayed reward was always presented on the right hand side of the screen. For the health block the option for immediate sickness was always displayed on the left hand side of the screen and the option for delayed sickness was always displayed on the right hand side of the screen. The word 'NOW' always appeared above the immediate option on the left side and 'In 10 years' or 'In 15 years' appeared above the delayed option on the right side. The number 50 appeared in brackets beside the word 'NOW' in the 'future condition' block and the numbers 60 or 65 appeared in brackets beside 'In 10 years' and 'In 15 years' respectively, in the 'future condition' block. Trials consisted of choices in which either a large or a small discrepancy existed between alternatives. Four choice pairs were classed as small disparity and four choice pairs were classed as large disparity for each task. For the financial task choices categorised as small disparity were as follows, 12, 000 - 30, 000, 14,000 – 28, 000, 16,000 – 26,000 and 18, 000 – 24,000 and choices categorised as large disparity were as follows; 12,000 – 60,000, 14, 000 – 58, 000, 16,000 – 56, 000 and 18,000 – 54, 000. For the health task choices categorised as small disparity were as follows; 3 weeks – 4 weeks, 2 weeks – 4 weeks, 3 weeks – 6 weeks and 1 week – 4 weeks and choices categorised as large disparity were as follows; 1 week – 8 weeks, 1 week – 6 weeks, 2 weeks – 8 weeks and 3 weeks – 8 weeks.

### ***Procedure***

Individual electrodes were adjusted to achieve an impedance level of less than 10k $\Omega$ . Participants were seated in a copper-plated electrically shielded cubicle (150cm X 180cm) half a metre from the computer monitor and had access to a mouse for responses.



A practice block preceded each test block. Each practice block consisted of eight sample choices taken from the test blocks. Instructions were presented on the computer screen.

### *Financial Task*

The financial task was sub-divided into two blocks, a 'present condition' block and a 'future condition' block. The financial task consisted of 128 trials per block. Trials consisted of choices in which either a large or a small discrepancy existed between alternatives. As described above, four choice pairs were classed as small disparity, e.g. 12,000 – 30,000 and four choice pairs were classed as large disparity, e.g. 12,000 – 60,000. Each of these choices were repeated 8 times in random order for 'now versus in 10 years' and 'now versus in 15 years'. Participants were advised that they would be asked to choose between different levels of financial gain.

*Present Condition Block:* After a short practice block, the 'present condition' block was divided into 'now versus in 10 years' and 'now versus in 15 years'. Participants were instructed to press the left mouse button if they preferred the immediate option or the right mouse button if they preferred the deferred option. Participants were also instructed that the immediate option would always be displayed on the left side of the screen and that all monetary amounts were displayed in Euro. There were 64 trials in total for the 'now versus in 10 years' section and 64 trials in total for the 'now versus in 15 years section'.

*Future Condition Block:* The 'future condition' block followed the same format as the 'present condition' block, however participants were given an additional instruction at the beginning of the block, 'we would like you to imagine that you are 50 YEARS OLD.'

What choices do you think you would make at 50 YEARS OLD as opposed to your current age?'. The number of trials was the same for the 'future condition' block as for the 'present condition' block.

### *Health Task*

Identical to the finance task, the health task was sub-divided into two blocks, a 'present condition' block and a 'future condition' block and consisted of 128 trials per block, of choices in which either a large or a small discrepancy existed between alternatives. Four choice pairs were classed as small disparity, e.g. 3 weeks – 4 weeks and four choice pairs were classed as large disparity, e.g. 1 week – 8 weeks. Each of these choices were repeated 8 time in random order for 'now versus in 10 years' and 'now versus in 15 years'. Participants were advised that they would be asked to choose between two options that represented different levels of discomfort arising from health treatment. Participants were asked to consider the following sickness, 'the symptoms are similar to those of severe flu i.e. a bad headache accompanied by nausea that renders you unable to perform your normal activities for the duration of the sickness'. Participants could choose to experience this sickness immediately for a number of weeks or they could choose to defer sickness for 10 years or 15 years and incur the symptoms for a longer number of weeks.

*Present Condition Block:* After a short practice block, the 'present condition' block was divided into 'now versus in 10 years' and 'now versus in 15 years'. Participants were instructed to press the left mouse button if they preferred the immediate option or the right mouse button if they preferred the deferred option. Participants were also instructed that the immediate option would always be displayed on the left side of the screen and

duration of sickness would always be displayed in weeks. There were 64 trials in total for the ‘now versus in 10 years’ section and 64 trials in total for the ‘now versus in 15 years’ section

*Future Condition Block:* The ‘future condition’ block followed the same format as the ‘present condition’ block, however participants were given an additional instruction at the beginning of the block, ‘we would like you to imagine that you are 50 YEARS OLD. What choices do you think you would make at 50 YEARS OLD as opposed to your current age?’. The number of trials was the same for the ‘future condition’ block as for the ‘present condition’ block.

For both the financial and health blocks, E-Prime© logged response times for each participant and sent TTL triggers to the EEG acquisition PC to allow stimulus presentations (stimulus type) and responses (immediate/delayed) to be logged in real time on the EEG recording. Response times were measured as the time between presentation of the stimulus and the response and were recorded for all trials.

### ***Data Analysis***

#### *Electrophysiological Setup and Recording:*

The EEG activity was recorded with tin electrodes (BrainVision©) mounted in an elastic cap fastened with a chest strap (Easy-Cap©). EEG data were collected from 128 scalp sites, using the extended version of the International 10-20 system for electrode placement (32). The reference electrode was located on the nasion at the tip of the nose. Vertical and horizontal eye movements were recorded using electrooculography (EOG).

VEOG was recorded from electrodes located above and below the left eye and HEOG was recorded from electrodes positioned at the outer canthus of each eye. Blinks were averaged off-line and a blink reduction algorithm was applied to the data. This algorithm involved automatic artifact correction (33,34). The impedance level was kept to below 10k $\Omega$  in all cases. EEG activity was amplified using a band-pass of 0.16-100Hz and a gain of 1000. The conversion rate was 2000Hz per channel and the range was 150mV. The amplifier used was supplied by Brainvision $\text{\textcircled{C}}$ .

*Behavioural Data:*

Response latencies were calculated automatically by E-Prime $\text{\textcircled{C}}$  and average response times were collated in E-Prime $\text{\textcircled{C}}$  for each domain under the following classification, 10 small immediate, 10 small delayed, 10 large immediate, 10 large delayed, 15 small immediate, 15 small delayed, 15 large immediate and 15 large delayed for both the 'present condition' and the 'future condition'. Response frequencies for each category were also collated in E-Prime $\text{\textcircled{C}}$ .

In the health domain, individuals' time preferences are revealed by how much longer they are willing to be ill in exchange for a delay in the onset of illness. The implied discount rate therefore can be calculated based on the difference in utility between two choices (A: immediate or B: delayed). The utility can be specified by the discrete choice model of the following form:

$$UB - UA = \beta_0 + \beta_1 (\textit{tradeoff}) + \beta_2 \textit{onset} + \varepsilon$$

The difference in utility of the immediate choice and delayed choice depends on the tradeoff of the duration of illness and the onset or the year in which the ill state occurs. The ratio of the coefficients of tradeoff versus the intercept and tradeoff versus onset indicates how much longer each participant is willing to be ill for some delay (10 or 15 years) in one specific year of onset (now or 50 years). Therefore, the implied discount rate is a function of the duration of illness and the ratio of the coefficients.

$$R_{\text{now}} = \left( \frac{\text{days} - \frac{\beta_0}{\beta_1}}{\text{days}} \right)^{\frac{1}{10}} - 1; \quad R_{50y} = \left( \frac{\text{days} - \frac{\beta_0 + \beta_2}{\beta_1}}{\text{days}} \right)^{\frac{1}{10}} - 1.$$

Likewise, by substituting the duration of illness by the amount of stake, we can get the individual implied discount rate in the financial domain (35).

*ERP Data:*

Recordings were notch filtered off line at 50Hz. EEG data were digitized at a sampling rate of 500 and were averaged offline using Brain Electrical Source Analysis software (BESA©). Stimulus-locked average ERPs were obtained by averaging the EEG using stimulus presentation as the trigger, epochs of 1100ms length were used, starting at – 100ms from stimulus presentation until 1000ms after stimulus presentation. 8 separate averaged ERPs were created based on the possible combinations of the stimulus presented and the participant’s response. These averaged ERPs are as follows, for ‘now versus 10 years’; 10 small immediate, 10 small delayed, 10 large immediate and 10 large

delayed and for 'now versus 15 years'; 15 small immediate, 15 small delayed, 15 large immediate and 15 large delayed.

Source waveforms were plotted in BESA©. Topographical voltage maps were generated in BESA© for all electrode sites and after visual inspection and analysis, 3 sites were chosen for further statistical analysis (Pz, FCz and P4). Averaged ERPs for each of these 3 sites were further analysed using repeated measures ANOVAs and paired samples t-test were used to compare AUC results for each of the 3 main components (N1, P2, P3) across each domain (finance and health) for each condition ('present condition' and 'future condition').

Possible cortical generators of scalp recorded potentials were analysed using BESA© software. BESA© uses a least squares fitting algorithm which is operator dependant. Dipoles were added to create a possible model for ERP data at each of the 3 chosen sites. A four shell ellipsoidal head model was employed and model fit was assessed by Residual Variance (RV).

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## **Figure Legend**

**Figure 1** A: Bar graphs showing mean frequency of responses for finance (left) and health (right) domains

B: Bar graph showing mean reaction times for finance (left) and health (right) domains

**Figure 2** Waveforms and corresponding scalp topographies for Finance domain and Health domain (A) Pz at 160 ms post stimulus (B) FCz at 190ms post stimulus (C) P4 at 300ms post stimulus

**Figure 3** MRIs showing dipole solutions for posterior P2 (170-210ms) for (A) Finance Overall and (B) Health Overall and Waveforms and MRIs for posterior P2 for (C) Finance Now and Finance 50 and (D) Health Now and Health 50

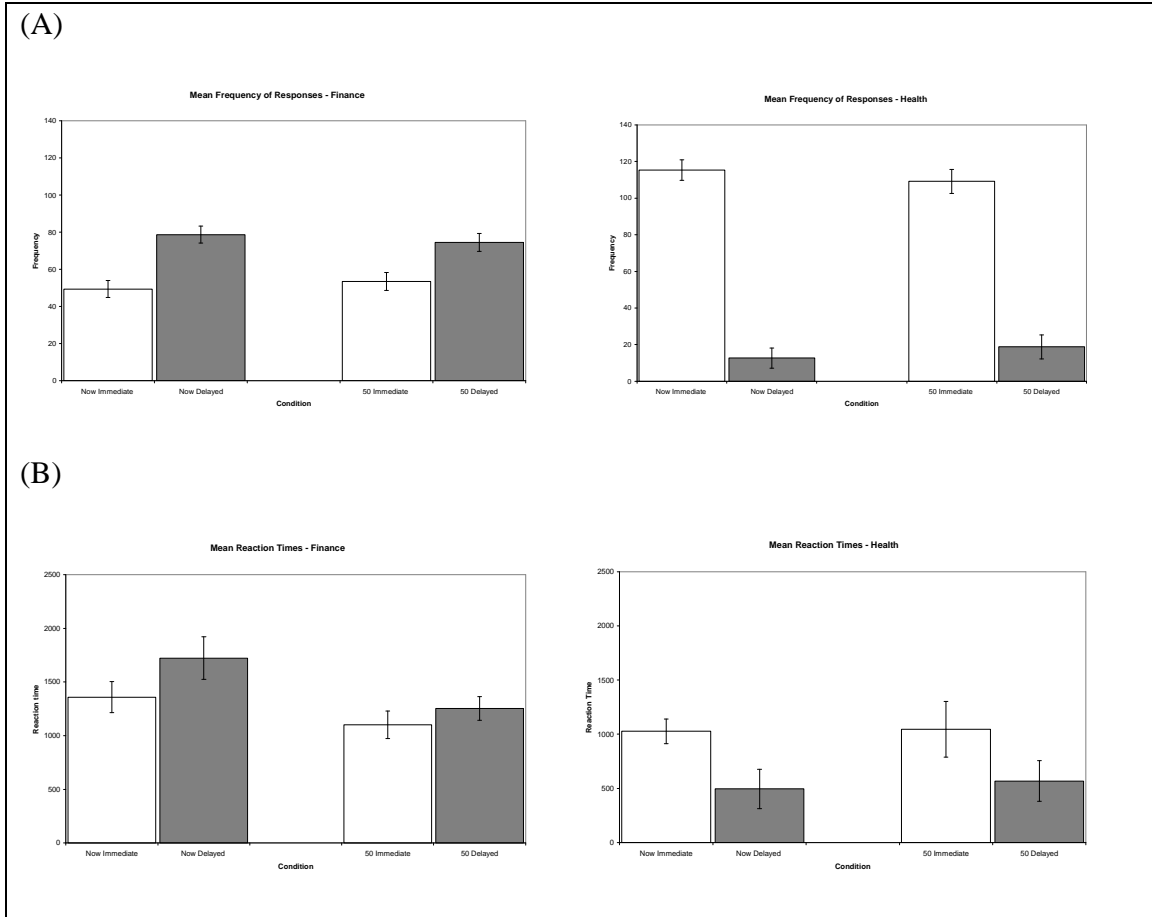


Figure 1: (A) Bar graph showing mean frequency of responses for finance (left) and health (right) domains (B) Bar graph showing mean reaction times for finance (left) and health (right) domains

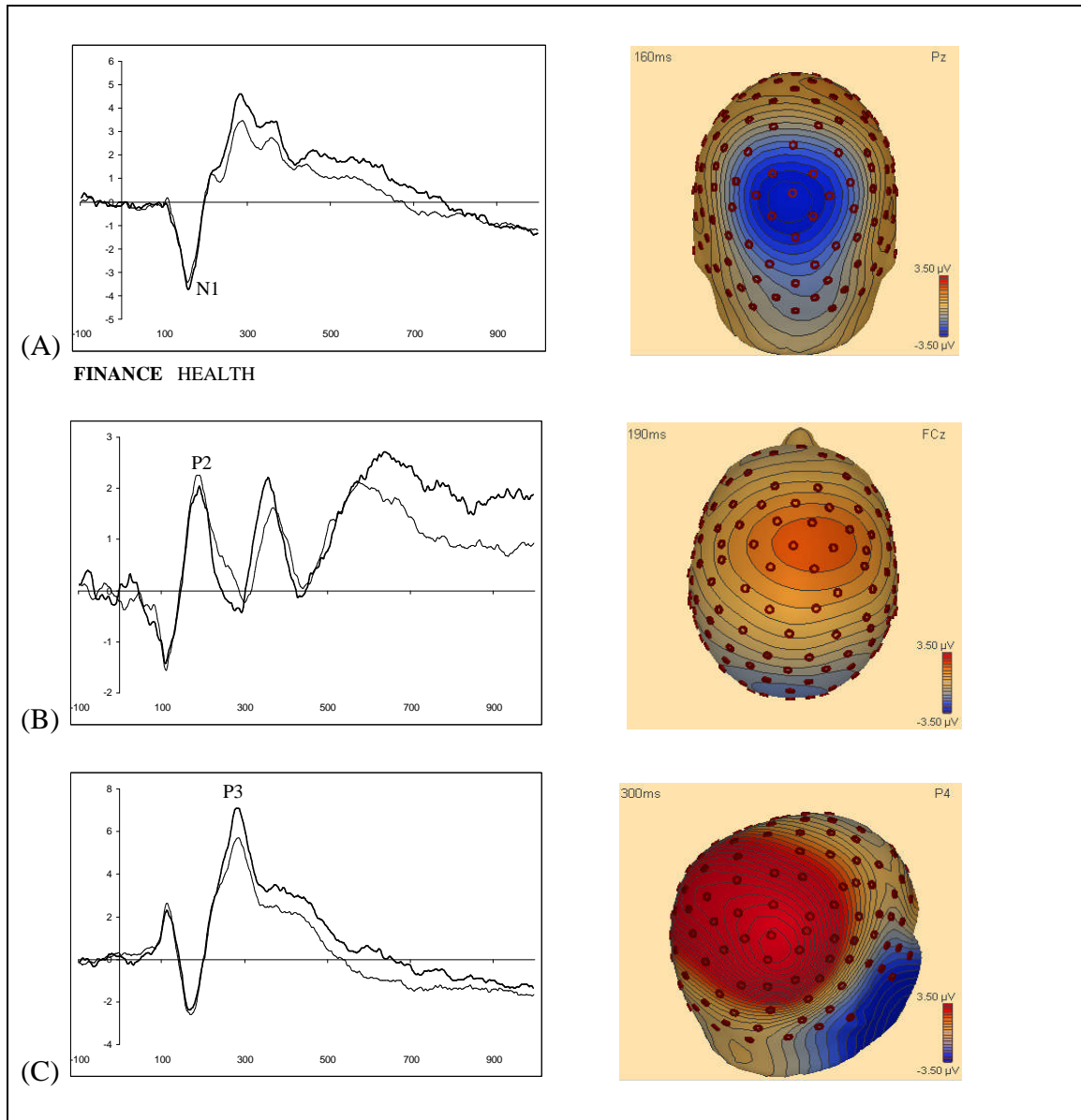


Figure 2: Waveforms and corresponding scalp topographies for Finance domain and Health domain (A) Pz at 160 ms post stimulus (B) FCz at 190ms post stimulus (C) P4 at 300ms post stimulus

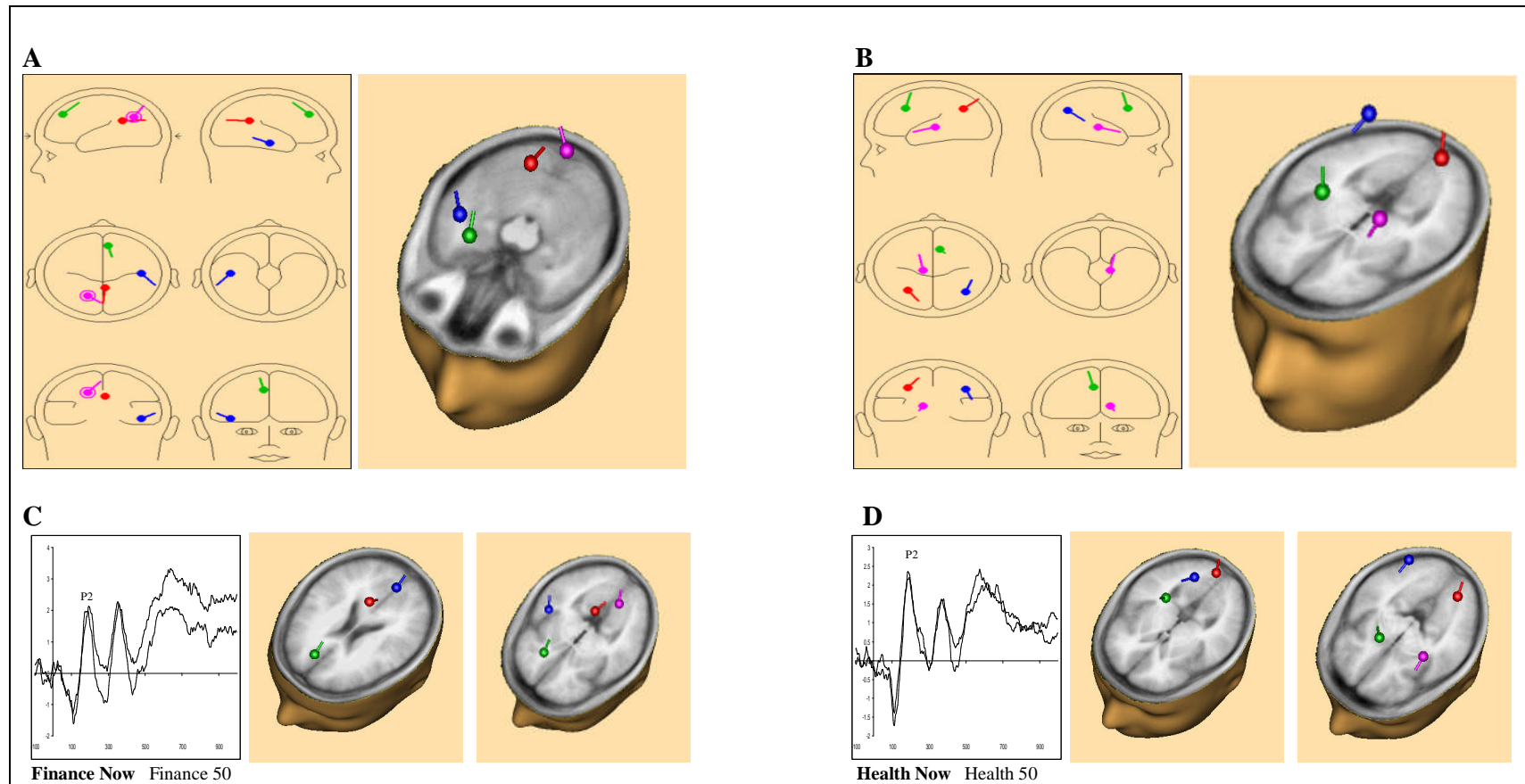


Figure 3: MRIs showing dipole solutions for posterior P2 (170-210ms) for (A) Finance Overall and (B) Health Overall and Waveforms and MRIs for posterior P2 for (C) Finance Now and Finance 50 and (D) Health Now and Health 50

### **Table Legend**

**Table 1** Regression analysis for health and financial discounting

**Table 2** Source localization results for N1 epoch (140-180ms) and P3 epoch (280-320ms)  
for each condition

Table 1: Regression analysis for health and financial discounting

COEFFICIENT	(1) Health	(2) Finance
onset	0.379** (0.151)	-0.212*** (0.069)
Health Difference	-2.484*** (0.333)	
Finance Difference		2.973*** (0.194)
Constant	0.192 (0.327)	-2.080*** (0.236)
Observations	640	1920
Number of subject	5	15
R-squared	.	.

Standard errors in parentheses  
 \*\*\* p<0.01, \*\* p<0.05, \* p<0.1

Table 2: Source localization results for N1 epoch (140-180ms) and P3 epoch (280-320ms) for each condition

	<b>Finance Overall</b>	<b>Health Overall</b>	<b>Finance Now</b>	<b>Finance 50</b>	<b>Health Now</b>	<b>Health 50</b>
<b>N1 (140-180ms)</b>	<p>Left Parietal Lobe, Precuneus (BA 19)</p> <p>Right Middle Temporal Gyrus (BA 37)</p> <p>Right Medial Frontal Gyrus (BA 8)</p> <p>Right Parietal Lobe, Precuneus (BA 7)</p> <p><i>R.V.=5.065%</i></p>	<p>Left Parietal Lobe, Precuneus (BA 19)</p> <p>Right Middle Temporal Gyrus (BA 39)</p> <p>Right Cingulate Gyrus (BA 24)</p> <p>Right Parietal Lobe, Precuneus (BA 19)</p> <p><i>R.V.=3.839%</i></p>	<p>Left Occipital Lobe, Cuneus (BA 19)</p> <p>Right Middle Temporal Gyrus (BA 37)</p> <p>Left Middle Frontal Gyrus (BA 10)</p> <p>Right Parietal Lobe, Precuneus (BA 7)</p> <p><i>R.V.=7.134%</i></p>	<p>Left Parietal Lobe, Precuneus (BA 19)</p> <p>Right Temporal Lobe, Sub-Gyral (BA 37)</p> <p>Left Medial Frontal Gyrus (BA 9)</p> <p>Right Parietal Lobe, Precuneus (BA 7)</p> <p><i>R.V.=5.719%</i></p>	<p>Left Parietal Lobe, Precuneus (BA 19)</p> <p>Right Superior Temporal Gyrus (BA 22)</p> <p>Right Cingulate Gyrus (BA 24)</p> <p>Right Parietal Lobe, Precuneus (BA 19)</p> <p><i>R.V.=4.169%</i></p>	<p>Left Superior Occipital Gyrus (BA 19)</p> <p>Right Occipital Lobe, Precuneus (BA 31)</p> <p>Right Cingulate Gyrus (BA 32)</p> <p>Right Parietal Lobe, Precuneus (BA 19)</p> <p><i>R.V.=4.729%</i></p>
<b>P3 (280-320ms)</b>	<p>Left Middle Temporal Gyrus (BA 39)</p> <p>Right Superior Temporal Gyrus (BA 22)</p> <p>Left Medial Frontal Gyrus (BA 9)</p> <p>Left Occipital Lobe, Cuneus (BA 18)</p> <p><i>R.V.=2.617%</i></p>	<p>Left Middle Temporal Gyrus (BA 39)</p> <p>Right Middle Temporal Gyrus (BA 19)</p> <p>Left Medial Frontal Gyrus (BA 9)</p> <p>Right Occipital Lobe, Cuneus (BA 7)</p> <p><i>R.V.=3.33%</i></p>	<p>Left Middle Temporal Gyrus (BA 39)</p> <p>Right Superior Temporal Gyrus (BA 22)</p> <p>Left Medial Frontal Gyrus (BA 9)</p> <p>Left Occipital Lobe, Cuneus (BA 18)</p> <p><i>R.V.=2.537%</i></p>	<p>Left Superior Temporal Gyrus (BA 39)</p> <p>Right Middle Temporal Gyrus (BA 39)</p> <p>Left Superior Frontal Gyrus (BA 9)</p> <p>Right Occipital Lobe, Cuneus (BA 18)</p> <p><i>R.V.=3.385%</i></p>	<p>Left Superior Temporal Gyrus (BA 39)</p> <p>Right Middle Temporal Gyrus (BA 37)</p> <p>Right Medial Frontal Gyrus (BA 9)</p> <p>Right Parietal Lobe, Precuneus (BA 31)</p> <p><i>R.V.=3.8%</i></p>	<p>Left Middle Temporal Gyrus (BA 37)</p> <p>Right Superior Temporal Gyrus (BA 22)</p> <p>Left Superior Frontal Gyrus (BA 10)</p> <p>Left Occipital Lobe, Cuneus (BA 19)</p> <p><i>R.V.=3.337%</i></p>