

2015

The Neural Correlates of Cognitive Behavioural Self-Regulation in Early Development

Andrew A. Nicholson
Western University

Niki Hosseini-Kamkar
Western University

Haley Fallowfield
Western University

J. Bruce Morton Ph.D
Western University

Follow this and additional works at: <http://ir.lib.uwo.ca/wupj>

 Part of the [Psychology Commons](#)

Recommended Citation

Nicholson, A. A., Hosseini-Kamkar, N., Fallowfield, H., & Morton, J. (2015). The Neural Correlates of Cognitive Behavioural Self-Regulation in Early Development. *Western Undergraduate Psychology Journal*, 3 (1). Retrieved from <http://ir.lib.uwo.ca/wupj/vol3/iss1/4>

This Article is brought to you for free and open access by Scholarship@Western. It has been accepted

The Neural Correlates of Cognitive Behavioural Self-Regulation in Early Development

Andrew A. Nicholson*
Niki Hosseini-Kamkar
Haley Fallowfield
Dr. J. Bruce Morton

To examine individual differences in cognitive behavioural self-regulation early in development, neural activity during a probabilistic learning task were correlated to measures of impulsivity in 8 normally developing children (10-12 years of age). Children completed a probabilistic learning task in an fMRI scanner and a delay discounting task, used to measure impulsivity, outside the scanner. Choices on the delay discounting task were modeled using a quasi-hyperbolic function, representing participant's subjective interpretation of a reward as a function of the delay period in which they must wait to obtain the reward. Subsequently, ventral striatum BOLD activity was correlated to individual performance during the probabilistic learning task, as well as to the quasi-hyperbolic model of the participant's delay discounting curve. It was hypothesized that the magnitude of ventral striatal activity would positively correlate to parameters of individual delay discounting functions. More impulsive individuals, denoted by steeper delay discounting functions, were expected to have more BOLD activity in the ventral striatum during the probabilistic learning task than those with a more modest delay discounting function, or who are less impulsive. Contrary to these predictions, ventral striatal activity was found to be negatively correlated to the quasi-hyperbolic function, modeling a developmental switch of cognitive processing in regard to self-regulation. The present results with regard to ventral striatal activity, have the potential to serve as a biomarker of individual differences in cognitive behavioural self-regulation in normally developing children.

It is important to identify vulnerabilities to cognitive risk factors in order to design and implement interventions that have the potential to modify an individual's developmental trajectory. Cognitive behavioural self-regulation is a crucial component of higher order executive functioning, and is defined as the ability to optimize positive outcomes and minimize aversive outcomes throughout one's life (Barutchu, Carter, Hester & Levy, 2013). Impulsivity and probabilistic learning broadly define two domains of cognitive behavioural self-regulation. Here, impulsivity involves the attenuated ability to refrain from present rewards in order to obtain larger ones in the future (Manuck, Flory, Muldoon & Ferrell, 2003).

Additionally, probabilistic learning involves the rate at which individuals can learn probabilities associated with rewards and negative stimuli (Barutchu, Carter, Hester & Levy, 2013). The present study aims to identify neural biomarkers that can predict individual differences in cognitive behavioural self-regulation.

In regard to the impulsivity component of cognitive behavioural self-regulation, high impulsivity has been associated with sub-optimal outcomes later in life. Impulsivity underlies much of human decision-making and is instrumental in several overlapping psychological constructs, such as self-regulation, impulse control and delay of gratification (Manuck et al., 2003). Those who strongly

*Initially submitted for Psychology 4850E at Western University. For inquiries regarding the article, please e-mail the corresponding author at anicho58@gmail.com.

COGNITIVE BEHAVIOURAL SELF-REGULATION

prefer smaller-value, immediate rewards over larger-value, deferred rewards are often generally impulsive, lack self-control and are more likely to engage in addictive behaviour (pathological gambling, cigarette smoking and drug/alcohol abuse) (Alessi & Petry, 2003; Brikel et al., 1999; Kirbey et al., 1999; Madden et al., 1997). Furthermore, in a study by Mischel and Soda (1988), children who were able to wait longer for rewards at age 4 or 5, were rated by parents 10 years later as more academically and socially competent, verbally fluent, rational, attentive and were able to deal with frustration and stress more effectively. Early identification of risk variables in regard to the learning domain of cognitive behavioural self-regulation are also important and pertinent to discuss.

Individuals learn to optimize positive outcomes and minimize aversive ones throughout their life. Tasks in which participants are required to learn reward and loss probabilities associated with ambiguous stimuli are often used to measure this domain of cognitive behavioural self-regulation. Using probabilistic learning tasks, depressed adult patients are characterized by an impaired ability to modulate behavior as a function of reward (Vrieze et al., 2013). Reduced reward learning is correlated with the increased likelihood that major depressive disorders will persist after 8 weeks of treatment (Vrieze et al., 2013). Furthermore, the neural correlates associated with dopamine and differences in the calibration of reward learning pathways between individuals have also been found to mediate cognitive behavioural self-regulation (Forbes et al. 2009). The present study investigates the neural foundation of two domains of cognitive behavioural self-regulation, impulsivity and probabilistic learning, in normally developing children. Therefore, it is first pertinent to discuss the literature examining the neural foundations of impulsivity in adult participants.

Delay discounting tasks are a standard behavioural measure of impulsivity in humans (Green & Myerson, 2004). Here, participants are presented with either a small immediate reward or a larger delayed reward and asked to choose between them. This process is repeated until a delay discounting parameter can be constructed a curve representing individual differences in the subjective interpretation of rewards based on their delay contingencies. This parameter shows individual differences in the value a reward holds based on the delay period in which the individual must wait to obtain it. In this regard, a steeper delay discounting function represents participants who are more likely to choose smaller rewards that are not delayed – or individuals who are more impulsive (Simpson & Vuchinich, 2000). In a study conducted by Gregorios-Pippas, Tobler and Schultz (2009), ventral striatal activity was shown to be associated with short-term reward value in adult humans when arbitrary point rewards were delayed by only a few seconds. Here, predictive reward value signals in the ventral striatum linearly decreased by a significant amount when rewards were delayed, illustrating less reward value. Furthermore, differential ventral striatal peak responses for discounters (those who report significantly discounting the subjective value of rewards that were delayed) and nondiscouter participants were found, in which peak responses in the ventral striatum decreased with increased reward delay for discounters, but not nondiscounters. Thus, it is apparent that the ventral striatal region in the brain is associated with delay discounting paradigms in which individuals are required to make decisions and regulate impulsive tendencies in order to maximize rewards. This suggests that the ventral striatal region plays an instrumental role in regard to predictive reward value (Gregorios-Pippas et al., 2009). Moreover, other studies have also found that individual differences are

COGNITIVE BEHAVIOURAL SELF-REGULATION

apparent when considering ventral striatal activity in discounters and nondiscounters.

When analyzing ventral striatal activity in adult participants during a delay discounting task, McClure, Laibson, Loewenstein and Cohen (2004) found that there was significantly higher ventral striatal activity in participants who were more likely to select a smaller, immediate monetary reward, compared to those participants who were more likely to choose a larger, delayed reward. Moreover, in a study conducted by O'Doherty (2004), it was found that activity in the ventral striatum increased in response to both the anticipation and receipt of rewarding stimuli, including both primary (e.g., food) and secondary (e.g., money) rewards. This is important when determining if the ventral striatum is only processing certain types of rewards – which has not been supported (O'Doherty, 2004). Notably, Stanger et al. (2013) show that during epochs in which children select larger, more delayed rewards, brain activity in the ventral striatum was positively correlated with delay discounting parameters such that a higher magnitude of ventral striatal activity was present in more impulsive individuals. Ventral striatal activity was not significantly correlated to measures of impulsivity for trials in which smaller, less delayed rewards were selected (Stanger et al., 2013). With regard to the former, in which the individual was selecting the most optimal choice, perhaps the ventral striatum is encoding the reward with exacerbated value in order for the more impulsive individual to select that choice (Stanger et al., 2013). This would also support findings by Gregorios-Pippas et al. (2009), who conceptualize the ventral striatum to be associated with reward value.

Empirical evidence also suggests that the ventral striatum is mediating reward processing in addition to behaviour during delay discounting tasks – thus influencing both domains of cognitive behavioural self-regulation

(Hariri et al., 2006). In Hariri et al.'s study (2006), investigators administered a card guessing game in an fMRI scanner. This card guessing game elicited either positive or negative feedback to adult participants after selecting a card. This task was meant to mimic the type of feedback one would receive during a probabilistic learning task. Generalized striatal activity was present on all feedback trial outcomes, regardless of feedback type, although there was greater ventral striatal activity during positive feedback trials (Hariri et al., 2006). Individual differences in delay discounting parameters, denoted by the hyperbolic function $\log[k]$, covaried significantly with the magnitude of ventral striatal activity on both positive and negative feedback trials, but again more so for the positive feedback condition. In summary, there was higher ventral striatal activity during positive and negative feedback trials in those individuals with steeper delay discounting functions, or those who were more impulsive, than those with a more modest delay discounting function or those who were less impulsive. In both cases, the steepness of the delay discounting function positively correlated with ventral striatal activity. It is therefore apparent that the ventral striatum is instrumental when making decisions regarding reward optimization, but also is required when behaving in a way that requires the regulation of impulsive tendencies. The positive and negative feedback conditions elicited in the Hariri et al.'s study (2006) are comparable, but not exactly the same as the feedback received during probabilistic learning tasks, where participants are required to learn reward contingencies of ambiguous stimuli.

Probabilistic learning tasks have been used to measure the ability of individuals to learn probabilities associated with rewards and negative stimuli in a way that optimizes life outcomes. In these tasks, ambiguous stimuli are presented to participants that are either associated with gains or losses of rewards. Each

COGNITIVE BEHAVIOURAL SELF-REGULATION

stimulus has varying probabilities corresponding to when they are rewarded. For example, one stimulus may be rewarded 80% of the time while another may only be rewarded 20% of the time. The goal of this task is to learn these probabilities as efficiently as possible such that the participant gains the most rewards. In a study conducted by Koch et al. (2008), a probabilistic learning task was administered to adult participants. During the reward-processing phase, where participants received feedback on the stimulus they selected, there was significant activation in the ventral striatum. Similarly, in a study by Pessiglione, Seymour, Flandin, Dolan and Frith (2006), patterns of bilateral ventral striatal activity were found in contrast images between gain and neutral stimuli, and also contrast images between loss and neutral stimuli in adult participants. Pessiglione et al. (2006) suggest that their results may represent a comparable signal in the ventral striatum to predict rewards and punishment avoidance and therefore this brain region may be associated with reward prediction error. Heekeren et al. (2007) also conducted a probabilistic learning task in fMRI on adult participants. During the decision making phase, BOLD activity in the ventral striatum increased monotonically as a function of learning such that the ventral striatum was most active when the participant expected to be rewarded for their decision with high certainty. In other words, when learning associated with a stimulus was the highest, ventral striatal activity was maximized. Furthermore, during the reward processing phase, ventral striatal activity was maximal when the participant was the most uncertain about the feedback they would receive for their choice (Heekeren et al., 2007).

In summary, it is apparent that the ventral striatum has a significant influence on the regulation of impulsivity and outcome learning in regard to cognitive behavioural self-regulation. Specifically, higher ventral striatal

activity is correlated to more impulsive individuals, or those with a steeper delay discounting function (Hariri et al., 2006). The ventral striatum has also been shown to code for short-term reward processing, with peak responses decreasing as a function of time in those who more heavily discount rewards (Gregorios-Pippas et al., 2009). Moreover, the ventral striatum has been shown to be significantly active during the reward processing phase of probabilistic learning tasks, in which the greatest activity occurs when the individual is most uncertain about the reward contingencies of a stimulus (Heekeren et al., 2007).

The objective of the present study was to identify neural biomarkers that can predict individual differences in cognitive behavioural self-regulation. We therefore modeled the effects of the ventral striatum on two components of cognitive behavioural self-regulation, probabilistic learning and impulsivity. Impulsivity was measured via a delay discounting paradigm, similar to the one used by Wilson et al. (2011). This task yielded a delay discounting parameter that which models individual differences in how participants subjectively discount rewards as a function of time — providing a measure of their impulsiveness. The neural mechanisms by which individuals learn to optimize positive outcomes and minimize aversive ones was measured via a probabilistic learning task in fMRI, similar to the one used by Pessiglione et al. (2006). In the present study, epochs of interest were temporal segments in which the participant received feedback on the stimuli they select in each trial. It is during the feedback segment of the probabilistic learning task that fMRI contrast images were generated for win and loss conditions for each participant. Inversely, the delay discounting paradigm was administered outside the scanner and correlations were analyzed between the delay discounting parameter and the relative BOLD activity in the

COGNITIVE BEHAVIOURAL SELF-REGULATION

ventral striatum during the feedback phase of the probabilistic learning task within the same participant.

Based on previous research, we present several predictions for the present study. Firstly, similar to results reported by Hariri et al. (2006) and Pessiglione et al. (2006), during win and loss trials in the feedback phase of the probabilistic learning task there was expected to be significant ventral striatal activity present. In this regard however, there should be a higher magnitude of ventral striatal activity during the win trials. Secondly, the magnitude of ventral striatal activity in children during the feedback phase of the probabilistic learning task should be positively correlated to the steepness of the delay discounting function within the same participant. It was expected that a larger magnitude of ventral striatal activity should be present among those with a steeper delay discounting function, or those who are more impulsive, than those with a more modest delay discounting function, or those who are less impulsive. To our knowledge, this is the first study to investigate how ventral striatal activity during a probabilistic learning task correlates to delay discounting parameters in normally developing children aged 10-12.

Method

Participants

Eight normally-developing prepubescent children (4 males and 4 females) between 10 and 12 years of age ($M = 133.75$ months, $SD = 12.75$ months) were recruited through the Child Development Participant Pool, maintained by the Department of Psychology at the University of Western Ontario. Participants and their parents/guardians were contacted via telephone, read a script describing the study and received an invitation to come into the lab for training. In the lab, informed consent and assent were obtained for both the behavioural delay

discounting task and the fMRI task after providing a letter of information. After completing the fMRI safety subsection in the letter of information with their parent/guardian, children who would be in danger during the fMRI acquisition were excluded (i.e., if they had metal implants). Children diagnosed or currently taking medication for ADD or ADHD were also excluded. Previous studies have found that ADD and ADHD can have significant implications on self-regulation (Shiels & Hawk, 2010). Furthermore, these children were excluded because the present study is investigating normally developing children. Parents/guardians were compensated a total of \$40 dollars cash (\$20 dollars per visit x two visits) and the children received a total of \$50 dollars in book vouchers (\$25 dollar voucher per visit x two visits). As a result of undesirable motion in the scanner, 16 participant's data were discarded.

Materials

Delay Discounting Task. The delay discounting behavioural task, designed by Wilson, Mitchell, Musser, Schmitt and Nigg (2011; see Appendix A), was used to measure the dependent variable of impulsivity in children outside the fMRI scanner. Children completed a short practice run to initially familiarize themselves with the paradigm. The task was administered via the computer software program E-Prime on an IMB laptop. Children were presented with two items simultaneously in each trial. The first item presented, on the left side of the screen, was a hypothetical monetary reward to be received now, varying on every whole dollar amount between \$0 and \$21 dollars. The second item presented, on the right side of the screen, was a standard hypothetical monetary reward of \$20 dollars in which the delay period varied between 0, 7, 30, 90 and 180 days. The delays and varying monetary rewards were paired together in all possible 110 combinations and presented randomly without replacement.

COGNITIVE BEHAVIOURAL SELF-REGULATION

Participants indicated their preference by laptop keyboard selection, in which Z denoted a reward on the left side of the screen, and M denoted a reward on the right side of the screen. The mean indifference point was defined as the average between the highest immediate value at which the smaller, immediate reward was selected and the lowest immediate value at which the larger, delayed reward was selected. In order to model the data using a function, the data was transposed such that immediate values less than the indifference point were coded in terms of response as 0 (preference for the larger, delayed reward) and values greater than or equal to the indifference point were coded in terms of response as 1 (preference for the smaller, immediate reward). These values were then inputted into a software program (Lau, 2011) which computed models fitting the data, yielding either a quasi-hyperbolic or hyperbolic discount function. The hyperbolic function fits the delay discounting data with only one parameter, K, where the probability of selecting the immediate option is equal to: $M / (1 + (K \times D))$, where M represents the magnitude of the reward, K is the parameter governing the degree of discounting and D is the delay period. Inversely, the quasi-hyperbolic function fits the delay discounting data with two variables, beta and delta. Both beta and delta contribute to the steepness of the function's slope, but beta represents more of a present bias towards an immediate reward. This model is called the beta-delta model and can fit the data more accurately (McClure et al., 2004). Here, the probability of selecting the immediate option is equal to: $(\beta \times \delta \times M)^D$, where M represents the magnitude of the reward, D represents the delay and beta/delta are constants between 1 and zero governing the degree of discounting.

Probabilistic Learning Task. After a short practice trial, participants performed a probabilistic learning task designed by Pessiglione, Seymour, Flandin, Dolan and Frith

(2006; see Appendix B). The task was administered during fMRI acquisition. This task was used in order to elicit positive, neutral and negative response feedback. Abstract stimuli were presented via E-Prime software and participants were required to learn their reward and loss contingencies. Three pairs of 6 stimuli represented either gain, loss or neutral feedback trials. The pair of stimuli presented together representing the gain trial had randomly assigned probabilities of being rewarded with 10 points. These reward probabilities were either 80% (with 20% chance of no reward) or 20% (with 80% chance of no reward), and stayed constant during the run. The goal was for participants to learn these probabilities and select the stimulus with the highest probability of gaining rewards. The pair of stimuli representing the loss trials had randomly assigned probabilities of losing 10 points. These loss probabilities were either 80% (with 20% chance of no loss) or 20% (with 80% chance of no loss), and stayed constant during the run. The final pair of stimuli representing the neutral trial consisted of two stimuli in which points were neither gained or lost. The pairs of stimuli were randomly assigned to one of the three categories of gain, loss and neutral at the beginning of each run, and changed each time a new run began. On each trial, one pair would be randomly displayed on the screen, to the left and right of a central fixation cross, with their relative position being counterbalanced across trials. The participants were required to choose either the left or the right stimulus using a button box in the scanner. To win points, the participants had to learn by trial and error, the stimulus–outcome association. Participants were instructed to gain as many points as possible. Although the rate at which participants can learn these probabilities associated with rewards is important, it should be noted that the epochs of interest for the present study were the time segments in which participants received feedback for their choices.

Procedure

Participants visited the laboratory on two separate occasions. During the first visit at Westminster Hall Laboratory, participants read the letter of information, and informed consent and assent were obtained with their parent/guardian present (see Appendices A, B and C). Participants were then trained in the mock fMRI (0-T) scanner to familiarize themselves with the environment and to mitigate any fear associated with the fMRI scanner. Participants completed the behavioural delay discounting task individually (Wilson et al., 2011). Subsequently, the child and parent/guardian received half of their compensation for their first visit, which lasted approximately 2-hours.

On the second visit, the children participated in the imaging procedure within the fMRI scanner, while they performed a computerized probabilistic learning task (Pessiglione, 2006). The scanning procedure consisted of a 1-hour MRI scan at the 3T-Siemens facility located at the Robarts Research Institute. Data that was collected in each scanning session consisted of 1000 T2*-weighted images collected as participants performed the computer-based probabilistic learning task administered with fMRI appropriate timing parameters, and 1 T1-weighted high-resolution anatomical image. Subsequently, the child and parent/guardian received the second half of their compensation for their second visit.

fMRI Data Acquisition. Data were collected using a 3 T Siemens Tim Trio MRI system fitted with a Siemens 32-channel head coil (Erlangen, Germany). Either 5 or 6 functional runs, each consisting of 130 whole-brain volumes were collected from each participant in a single scanning session. Functional volumes consisted of 32-slices (thickness = 3 mm) and were collected in an ascending interleaved order using a T2*-weighted echo-planar imaging sequence

(TR=2000 ms; TE= 30 ms; flip angle = 78°), with an in-plane matrix of 64 × 64 pixels and a 21.1 × 21.1 cm field of view, yielding a 3 mm × 3 mm × 3 mm voxel resolution. There were no gaps between slices. To assist in the visualization of functional analyses, a T1-weighted anatomical scan consisting of 192 slices (thickness = 1 mm) with an in-plane 256 × 256 matrix and a 21.1 × 21.1 cm field of view (yielding a 1 × 1 × 1 mm voxel resolution) was also collected as part of the same scanning session.

fMRI Data Preprocessing. In order to preprocess the data, Statistical Parametric Mapping (SPM8) software was used from the Wellcome Department of Cognitive Neurology, London within Matlab 7.10 (The Mathworks Inc., MA). Prior to preprocessing, motion parameters were calculated for each run. Inter-session alignment was used. Linear trend removal was applied to the time courses of motion-corrected functional runs. T1-weighted anatomical scans were spatially normalized to an EPI template in MNI (Montreal Neurological Institute) stereotactic space (Friston et al., 1995). T2*-weighted functional volumes were then automatically aligned to unwarped anatomical images by means of a gradient-based affine alignment algorithm. Functional volumes were then warped into MNI space by applying the parameters used to warp the anatomical images into MNI space. Functional volumes were then smoothed using an 8 mm full-width at half maximum Gaussian kernel.

Statistical Analysis. Statistical Parametric Mapping (SPM8), within Matlab 7.10 (The Mathworks Inc., MA) was used to analyze the data. Organized into win, null and loss feedback, whole-brain General Linear Models (GLM) based on feedback type were constructed yielding various β coefficients. β coefficients were constructed via separate boxcar functions, convolved with a two-gamma model of the haemodynamic response function to create

orthogonal predictors. β weights of each of the predictors were computed by means of a whole-brain random-effects (RFX) analysis. Contrast images were generated on t-value statistical parametric maps by subtracting β coefficients of null feedback trials from that of the β coefficients from win feedback trials (yielding brain activity for the win feedback trials). Contrast images were generated for loss feedback trials by subtracting the β coefficients of the null feedback trials from that of the β coefficients from loss feedback trials. Ventral striatum activity was localized by defining the anatomical region in Pickatlas (Maldjian et al., 2003).

Results

Group 2nd Level Analysis

To observe significant brain activity associated with the feedback segments of the probabilistic learning task, group level contrast images were generated for win versus loss trials, with an uncorrected $p < .05$. This group analysis revealed significant ventral striatal (VS) activity associated with wins versus losses, Figure 1. The coordinates of this ROI were used in the subsequent first level analysis.

Individual Differences 1st Level Analysis

The statistical threshold was lowered to $p < .99$ to observe individual differences in activity within the VS for the 8 participants. Using a cluster analysis sphere ($r = 3\text{mm}$), t -statistics were extracted from the ROI for each participant, in order to observe differences in the magnitude of brain activity, see Figure 2. The various t -statistics were analyzed in conjunction with the computed hyperbolic and quasi-hyperbolic functions modeling individual differences in delay discounting, see Table 1.

Ventral Striatum

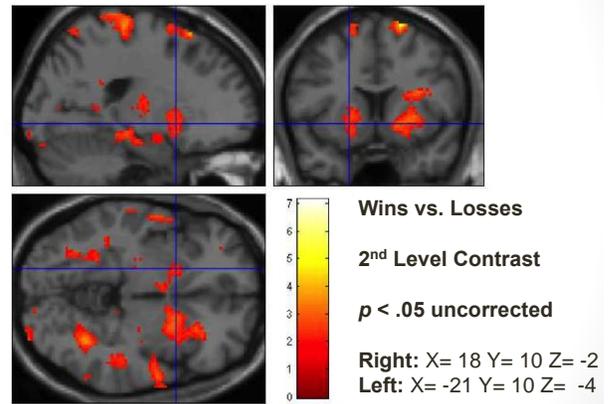


Figure 1. Group level contrast for wins versus losses among the 8 participants. Significant activity was found bilaterally for the ventral striatum, with an uncorrected $p < .05$. Coordinates of the region are in MNI space.

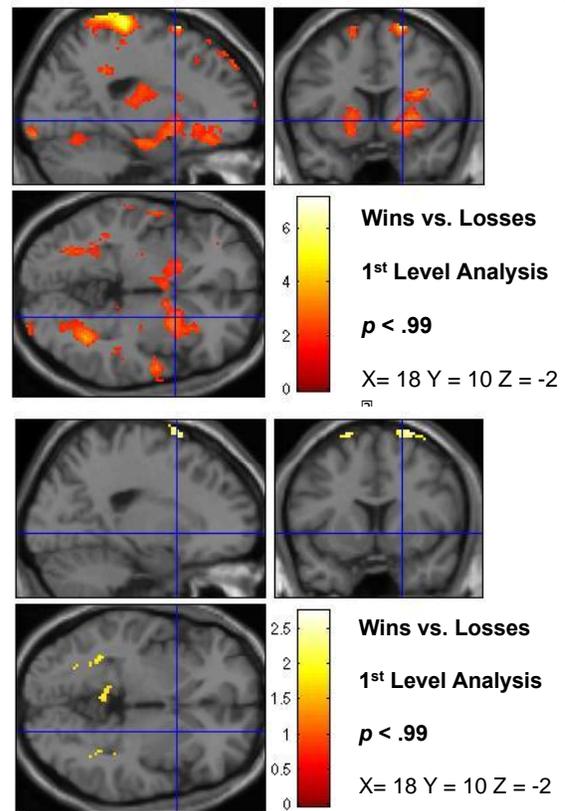


Figure 2. Differential brain activation in the ventral striatum among two participants, where the participant on the left shows significantly more activation than the one on the right. The statistical threshold was set at $p < .99$.

COGNITIVE BEHAVIOURAL SELF-REGULATION

Table 1

Descriptive Statistics for Parameters Fitting Delay Discounting Data and *t*-Statistics of Win Versus Loss Contrast Images

Variable	<i>M</i>	<i>SD</i>
K	.042	.051
Beta	.937	.326
Delta	.968	.041
Right Ventral Striatum	.803	.898
Left Ventral Striatum	.475	.805

Note. Beta and delta are the two variables in the quasi-hyperbolic model. K represents the hyperbolic parameter. Right and left ventral striatal *t*-statistics were extracted from win versus loss contrast images. High variance among individuals is apparent.

Hyperbolic Model. A multiple regression was computed to predict individual differences within the hyperbolic delay discounting parameter $\log[K]$ from the left and right VS win versus loss contrast image: $R = .642$ and $R^2 = .412$. Initial regression diagnostics showed no collinearity between the two predictors. This model was found to be non-significant, $F(2, 5) = 1.75, ns$. Neither variable significantly predicted the hyperbolic parameter K: left VS ($\beta = .161, t = 1.84, ns$) and right VS ($\beta = -.787, t = -.901, ns$). In order to observe trends in this initial data

more transparently, correlations between the predicted variable K, and the predictors, left and right VS activity, were investigated. Here a significant negative Pearson’s bivariate correlation was found between K and the right VS, $r(6) = -.639, p = .044$, and a non-significant negative correlation was found between K and the left VS, $r(6) = -.563, ns$, see Figure 3. All data points in these correlations yielded a maximum Cook’s distance of < 1 ($M = .181$), thus Figure 3 may be interpreted with confidence.

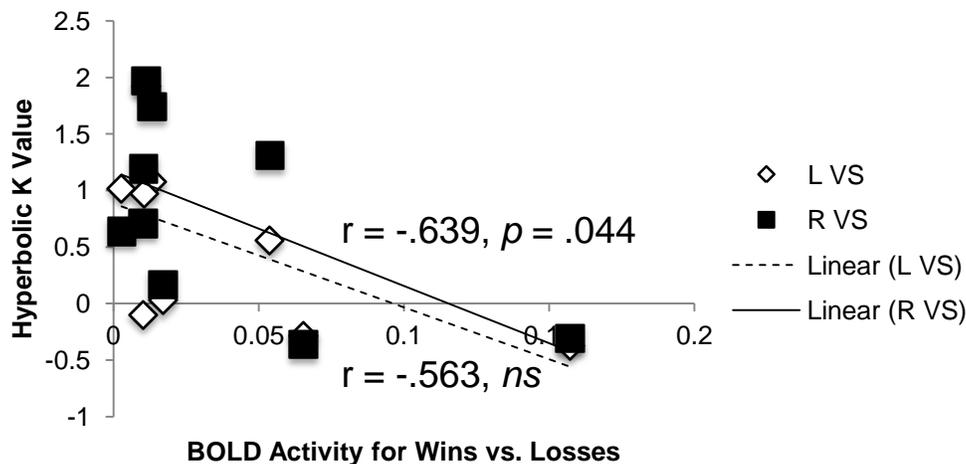


Figure 3. Scatterplot illustrating the correlation between the hyperbolic k parameter in relation to both right and left ventral striatum activity for wins versus losses among the 8 participants. There is a significant negative correlation between the right ventral striatum and K, and a non-significant negative correlation between the left ventral striatum and K.

COGNITIVE BEHAVIOURAL SELF-REGULATION

Quasi-hyperbolic Model. A multiple regression was computed to predict right VS individual differences in win versus loss contrast images from both beta and delta within the quasi-hyperbolic model, in which $R = .708$ and $R^2 = .501$. This model was found to be non-significant, $F(2, 5) = 2.51, ns$. Furthermore neither variable significantly predicted right VS activity: beta ($\beta = -.486, t = -1.03, ns$) and delta ($\beta = .268, t = .566, ns$). In order to observe trends in this initial data more transparently, correlations between the predicted variable right

VS, and the predictors, beta and delta, were investigated. Here, a significant negative Pearson's bivariate correlation was obtained between the right VS and beta, $r(6) = -.685, p = .030$, and a significant positive correlation was obtained between the right VS and delta, $r(6) = .629, p = .047$, see Figure 4. All data points in these correlations yielded a maximum Cook's distance of < 1 ($M = .171$), thus Figure 4 may be interpreted with confidence.

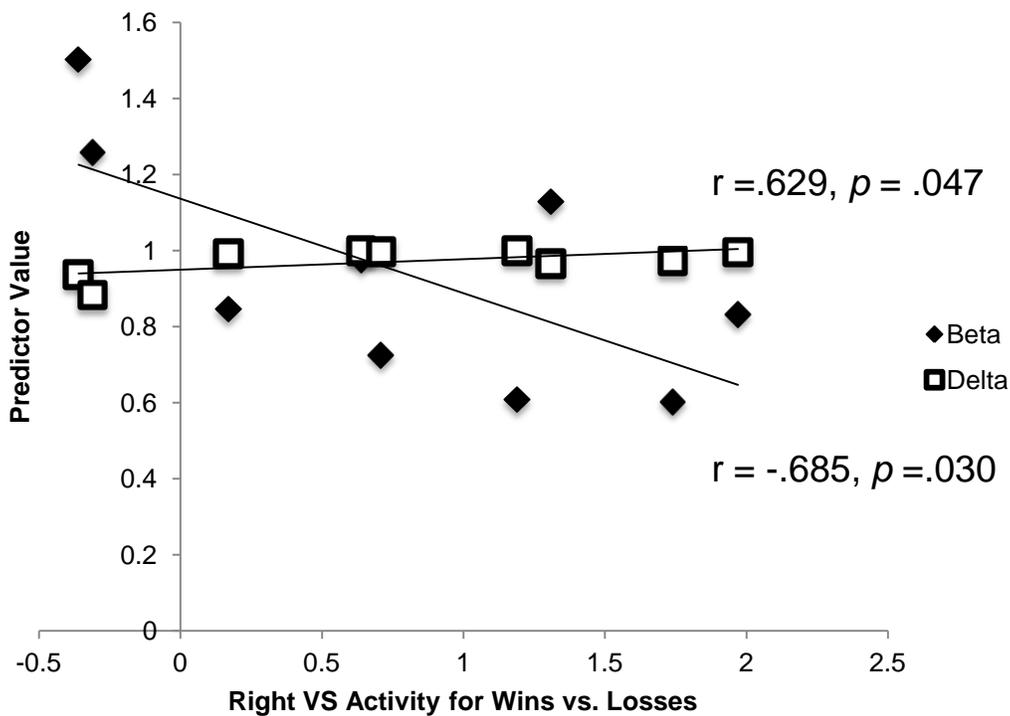


Figure 4. Scatterplot illustrating the correlation between both beta and delta in relation to right ventral striatum activity for wins versus losses among the 8 participants. There is a significant negative correlation between the right ventral striatum and beta, and a significant positive correlation between the right ventral striatum and delta.

Another multiple regression was computed to predict left VS individual differences in win versus loss contrast images from both beta and delta, where $R = .599$ and $R^2 = .359$. This model was found to be non-significant, $F(2, 5) = 1.40, ns$. Furthermore neither variable significantly

predicted left VS activity: beta ($\beta = -.353, t = -6.58, ns$) and delta ($\beta = .289, t = .539, ns$). Here a non-significant negative Pearson's bivariate correlation was obtained between the left VS and beta, $r(6) = -.568, ns$, and a non-significant positive correlation was found between the left

COGNITIVE BEHAVIOURAL SELF-REGULATION

VS and delta, $r(6) = .551, ns$, see Figure 5. All data points in these correlations yielded a maximum Cook's distance of < 1 ($M = .068$),

thus Figure 5 may be interpreted with confidence.

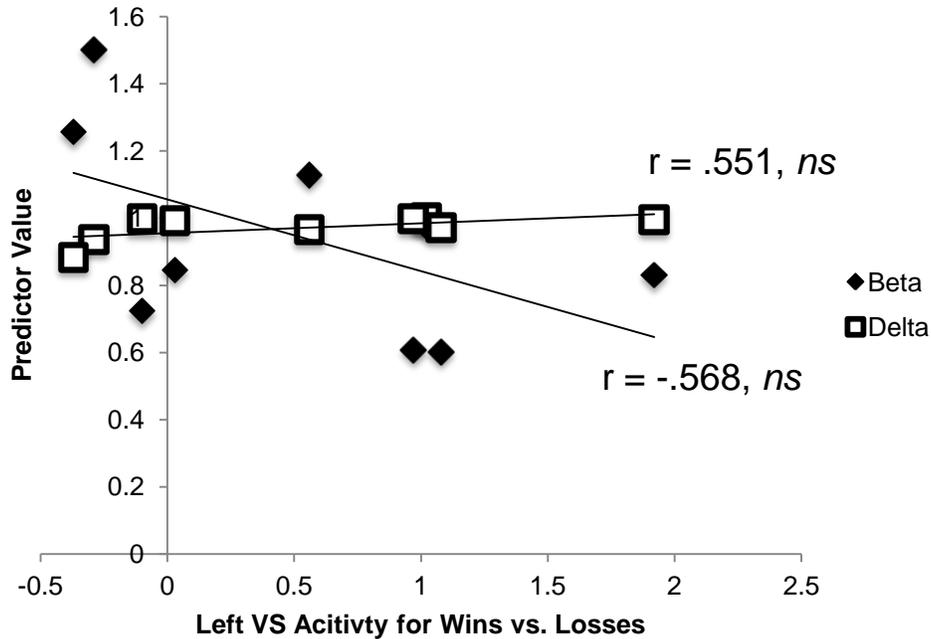


Figure 5. Scatterplot illustrating the correlation between both beta and delta in relation to left ventral striatum activity for wins versus losses among the 8 participants. The negative correlation between the left ventral striatum and beta, and the positive correlation between the left ventral striatum and delta, were found to be non-significant. However general trends are similar to that seen in the right ventral striatum.

Discussion

By identifying neural biomarkers early in life, one's developmental trajectory can be mediated if the variable in question will have detrimental effects on the individual later in life. The objective of the present study was to identify neural biomarkers that can predict individual differences in cognitive behavioural self-regulation. In line with our hypotheses, the ventral striatum was bilaterally associated with the probabilistic learning task employed when investigating feedback contrasts. This was similar to results found by Pessiglione et al. (2006), where patterns of bilateral ventral striatal

activity were found in contrast images between gain and neutral stimuli, and also contrast images between loss and neutral stimuli in adult participants.

Contrary to our hypotheses, the right ventral striatum was negatively correlated to the hyperbolic parameter K, and the left ventral striatum was not significantly correlated to the hyperbolic parameter K. Furthermore, the right ventral striatum exhibited a significant negative relationship to the quasi-hyperbolic beta-delta model. Similarly, the left ventral striatum did not illustrate a significant correlation to the beta-delta model. Therefore, a larger magnitude of ventral striatal activity was found among

COGNITIVE BEHAVIOURAL SELF-REGULATION

participants who were less impulsive. In sum, when using both models of delay discounting, right ventral striatal activity during a probabilistic learning task was effectively able to predict individual differences in delay discounting.

The present results are in direct contrast to the findings reported by Hariri et al. (2006), in which the hyperbolic parameter K illustrated a significant positive correlation to bilateral ventral striatal activity. Hariri et al. (2006) concluded that more impulsive individuals are characterized by exhibiting more ventral striatal activity during the feedback portion of their probabilistic task. The present study reports a significant negative relationship for only the right ventral striatum contrast images for wins versus losses during the feedback portion of the probabilistic learning task, for both the hyperbolic and quasi-hyperbolic functions. This relationship is unique because it is a negative correlation, and also because it is not bilateral. However, it should be noted that the paradigm employed by Hariri et al. (2006) was a card guessing game, and did not contain a learning component to the task. Therefore, the present study may be measuring differential neural processes, as reward probability contingencies are required to be learned. In support of Hariri et al.'s (2006) findings, Gregorios-Pippas et al. (2009) also reported differential ventral striatal activation slopes for discounter and nondiscounter participants, in which a higher magnitude of ventral striatum activity was present among more impulsive adult participants. Again, these results are in contrast to the present study's findings.

The present study's results suggest a developmental reversal of the neural mechanisms associated with cognitive behavioural self-regulation. Developmental switches have also been reported by Dumontheil et al. (2011), in which two catechol-*O*-methyltransferase (COMT) enzyme genotypes

(Met/Met and Val/-) produced optimal scores on a working memory task differentially depending on age. The COMT enzyme mediates the degradation of catecholamines – in particular dopamine. The Valine158Methionine (Val158Met) polymorphism leads to lower enzymatic activity and higher dopamine availability in Met carriers (for review, see Dumontheil et al., 2011). In contrast, the Met allele is associated with better performance and attenuated prefrontal cortex activation during working memory tasks in adults. In the study conducted by Dumontheil et al. (2011), there appeared to be a developmental switch at 11 years old. Prior to this age the Val/- genotype exhibited the highest scores on working memory tasks, and inversely, the Met/Met genotype exhibited higher scores on working memory tasks after 11 years of age (Dumontheil et al., 2011). Furthermore, the differences in working memory scores between the two genotypes became exacerbated as scores were examined increasingly before and increasingly after 11 years of age, and there were no difference between working memory scores at 11 years of age. Notably, tonic and phasic levels of dopamine (which have direct associations with COMT) have been found to mediate reward processing in the brain as well as goal directed behaviour, and thus may offer significant contributions to the pattern of results illustrated in the present study (Schultz, 2010).

Perhaps the present study's correlation between increased activity in the ventral striatum during the probabilistic learning task, with less impulsive measures on the delay discounting task, is because the ventral striatum is encoding feedback during learning as rewarding (Stanger et al., 2013). Stanger et al. (2013) show that during epochs in which children select larger, more delayed rewards, brain activity in the ventral striatum was positively correlated with delay discounting parameters such that a higher magnitude of ventral striatal activity was present

COGNITIVE BEHAVIOURAL SELF-REGULATION

in more impulsive individuals. When the individual was selecting the most optimal choice, Stanger et al. (2013) suggest the ventral striatum is encoding the reward with exacerbated value in order for the more impulsive individual to select that choice. This would also support findings by Gregorios-Pippas et al. (2009), who conceptualize the ventral striatum to be associated with reward value.

Critically, there is a protracted development of the prefrontal cortex (PFC) in adolescence (e.g., Bunge et al., 2002), and in turn PFC mediated executive functioning related to cognitive behavioural self-regulation. Thus, children might be employing the use of other brain regions (that would not otherwise be utilized in adulthood) during the tasks used in the present study. Hence, the current results illustrating greater ventral striatal activity among participants who are less impulsive, may be a result of less PFC cognitive resources available, due to the immature state of the PFC in children. In support of this, the review by Hammerer and Eppinger et al. (2012) conclude that learning impairments in children can primarily be attributed to deficits in executive control, which may result due to the protracted development of the dorsomedial and lateral prefrontal cortices.

Caution should be employed when interpreting these correlations as all multiple regression equations for both the hyperbolic and quasi-hyperbolic functions were found to be non-significant. Furthermore the β values for all variables in all multiple regression equations were found to be non-significant. This is probably due to the fact that there is low power in this preliminary study as only 8 participants were analyzed. Notably, the significance of these multiple regression models may be exacerbated pending subsequent analysis of future participants. Correlations among the ventral striatum and the delay discounting models are highlighted, as observing the trends of these

relationships may be the most informative statistical analysis at this point in the study.

Subsequent analyses should include an investigation of early versus late trial contrast images to observe differential ventral striatum activity as a function of learning. Heekeren et al. (2007) reported that during the decision making phase of a probabilistic learning task, ventral striatal activity was maximized when a stimulus was chosen with the most certainty, or when learning was maximal. Furthermore, during the reward processing phase, there was maximal ventral striatum activity when uncertainty about the feedback the participant would receive was the highest. This variability in ventral striatal activity may have significant effects on contrast images when grouping them together over the administration of the task, thereby not taking into consideration these learning effects (Heekeren et al., 2007). Therefore, future studies should investigate early versus late trials, in addition to learning associated certainty of response during feedback and selection. In relation, it may be also be valuable to administer the same probabilistic card guessing game, employed in the study by Hariri et al. (2006), in order to directly compare these two studies in terms of a developmental switch of cognitive functioning. This is critical as Hariri et al.'s (2006) paradigm did not contain a learning component to the task. Furthermore, it would be interesting to investigate levels of dopamine via PET while administering the task employed by the present study.

In conclusion, the results of the present study are impactful with regard to successfully mediating developmental outcomes of individuals. If biomarkers can be identified early in development, and the relationship between these biomarkers and cognitive behavioural self-regulation elucidated, developmental trajectories may be optimized. This would have significant applications as Mischel and Soda (1988) illustrated that children who were able to wait

COGNITIVE BEHAVIOURAL SELF-REGULATION

longer for rewards at age 4 or 5, were rated by parents 10 years later as more academically and socially competent, verbally fluent, rational, attentive and were able to deal with frustration and stress more effectively, and those who strongly prefer smaller-value, immediate rewards over larger-value, deferred rewards are often generally impulsive, lack self-control and are more likely to engage in addictive behaviour (Alessi & Petry, 2003; Brikel et al., 1999; Kirbey et al., 1999; Madden et al., 1997). Critically reduced reward learning is also correlated with the increased likelihood that major depressive disorders will persist after 8 weeks of treatment (Vrieze et al., 2013). Thus, early identification of risk variables in regard to the learning and impulsivity domains of cognitive behavioural self-regulation are valuable, and may exhibit unique patterns of brain activity in children.

First Received: 10/10/2014

Final Revision Received: 03/31/2015

References

- Barutchu, A., Carter, O., Hester, R., & Levy, N. (2013). Strength in cognitive self-regulation. *Frontiers in Psychology, 4*, 174.
- Bickel, W.K., Odum, A.L., & Madden, G.J. (1999). Impulsivity and cigarette smoking: delay discounting in current, never, and ex-smokers. *Psychopharmacology, 146*, 447–454.
- Bunge, S.A., Dudukovic, N.M., Thomason, M.E., Vaidya, C.J., & Gabrieli, J.D.E. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron, 33*, 301–311.
- Dumontheil, I., Roggeman, C., Ziermans, T., Peyrard-Janvid, M., Matsson, H., Kere, J., & Klingberg, T. (2011). Influence of the COMT genotype on working memory and brain activity changes during development. *Biological Psychiatry, 70*, 222–229.
- Forbes, E. E., Brown, S. M., Kimak, M., Ferrell, R. E., Manuck, S. B., & Hariri, A. R. (2009). Genetic variation in components of dopamine neurotransmission impacts ventral striatal reactivity associated with impulsivity. *Molecular Psychiatry, 14*, 60–70.
- Friston, K.J., Ashburner, J., Frith, C.D., Poline, J.B., Heather, J.D., Frackowiak, R.S.J., (1995). Spatial registration and normalisation of images. *Human Brain Mapping, 2*, 165–189.
- Green, L., & Myerson, J. (2004) A discounting framework for choice with delayed and Probabilistic rewards. *Psychology Bulletin, 130*, 769 –792.
- Gregorios-Pippas, L., Tobler, P.N., & Schultz, W. (2006). Short-term temporal discounting of reward value in human ventral striatum. *Journal of Neurophysiology, 101*, 1507–23.
- Hämmerer, D., & Eppinger, B. (2012). Dopaminergic and prefrontal contributions to reward-based learning and outcome monitoring during child development and aging. *Developmental Psychology, 48*, 862–874.
- Hariri, A.R., Brown, S.M., Williamson, D.E., Flory, J.D., de Wit, H., & Manuck, S.B. (2006). Preference for immediate over delayed rewards is associated with magnitude of ventral striatal activity. *Journal of Neuroscience, 26*, 13213–13217.
- Heekeren, H. R., Wartenburger, I., Marschner, A., Mell, T., Villringer, A., & Reischies, F. M. (2007). Role of ventral striatum in reward-based decision making. *Neuroreport, 18*, 951–955.
- Koch, K., Schachtzabel, C., Wagner, G., Reichenbach, J. R., Sauer, H., & Schlösser, R. (2008). The neural correlates of reward-related trial-and-error learning: An fMRI study with a probabilistic learning task. *Learning & Memory, 15*, 728–732.
- Lau, B. (2011). Matlab code to estimate temporal discount function [Software]. Available from <http://www.subcortex.net/research/code/code-temporal-discounting>
- Madden, G.J., Petry, N.M., Badger, G.J. & Bickel, W.K. (1997). Impulsive and self- control choices in opioid-dependent patients and non-drug-using control participants: drug and monetary rewards. *Experimental Clinical Psychopharmacology, 5*, 256 –262.
- Manuck, S.B., Flory, J.D., Muldoon, M.F. & Ferrell, R.E. (2003). A neurobiology of intertemporal choice. *Time and decision: economic and psychological perspectives on intertemporal choice*. pp 139 –172. New York: Sage.

COGNITIVE BEHAVIOURAL SELF-REGULATION

- Maldjian, J.A., Laurienti, P.J., Kraft, R.A., Burdette, J.H. (2003). An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI data sets. *Neuroimage*, *19*, 1233–1239.
- McClure, S.M., Laibson, D.I., Loewenstein, G. & Cohen, J.D. (2004). Separate neural systems value immediate and delayed monetary rewards. *Science*, *306*, 503–507.
- Mischel, W., Shoda, Y., & Peake, P. K. (1988). The nature of adolescent competencies predicted by preschool delay of gratification. *Journal of Personality and Social Psychology*, *54*, 687-696.
- O’Doherty, J.P. (2004). Reward representations and reward-related learning in the human brain: insights from neuroimaging. *Neurobiology*, *14*, 769.
- Pessiglione, M., Seymour, B., Flandin, G., Dolan, R. J., & Frith, C. D. (2006). Dopamine-dependent prediction errors underpin reward-seeking behaviour in humans. *Nature*, *442*, 1042-1045.
- Schultz, W. (2010). Dopamine signals for reward value and risk: Basic and recent data. *Behavioral and Brain Functions*, *6*, 24-24.
- Shiels, K., & Hawk, L. W. (2010). Self-regulation in ADHD: The role of error processing. *Clinical Psychology Review*, *30*, 951-961.
- Simpson, C.A. & Vuchinich, R.E. (2000). Reliability of a measure of temporal discounting. *Psychology Rec*, *50*, 3–16.
- Stanger, C., Elton, A., Ryan, S. R., James, G. A., Budney, A. J., & Kilts, C. D. (2013). Neuroeconomics and adolescent substance abuse: Individual differences in neural networks and delay discounting. *Journal of the American Academy of Child and Adolescent Psychiatry*, *52*, 747-755.
- Vrieze, E., Pizzagalli, D. A., Demyttenaere, K., Hompes, T., Sienaert, P., de Boer, P., & Claes, S. (2013). Reduced reward learning predicts outcome in major depressive. *Biological Psychiatry*, *73*, 639.
- Wilson, V. B., Mitchell, S. H., Musser, E. D., Schmitt, C. F., & Nigg, J. T. (2011). Delay discounting of reward in ADHD: Application in young children. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *52*, 256-264.

COGNITIVE BEHAVIOURAL SELF-REGULATION

Appendix A

Delay Discounting Task Visual Stimuli (Wilson, Mitchell, Musser, Schmitt, & Nigg, 2011)

Description.

Participants were required to choose between a varied immediate reward (received now) and a delayed reward in which the delay contingency is varied but the reward is held constant (\$20 dollars).



COGNITIVE BEHAVIOURAL SELF-REGULATION

Appendix B

Probabilistic Learning Task Visual Stimuli (Pessiglione, 2006)

Description.

This is a trial and error task in which ambiguous stimuli are presented in pairs and each are rewarded with varying probabilities. Participants are required to learn to the probabilities associated with the stimuli's reward contingencies in order to maximize the amount of rewards received and avoid losses. Shown below, the reward probabilities for the two stimuli are 80% (jacket) and 20% (bench).

