

Running Head: DELAY DISCOUNTING, INTELLIGENCE, & WORKING MEMORY

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Individual differences in delay discounting: Relation to intelligence, working memory, and
anterior prefrontal cortex

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Abstract

Lower delay discounting (better self-control) is linked to higher intelligence, but the basis of this relation is uncertain. To investigate the potential role of working memory processes (WM), we assessed delay discounting, intelligence (g), WM (span tasks, 3-back task), and WM-related neural activity (using fMRI) in 103 healthy adults. Delay discounting was negatively correlated with g and WM. Of note, WM explained no variance in delay discounting beyond that explained by g , suggesting that processes through which WM relates to delay discounting are shared by g . WM-related neural activity in left anterior prefrontal cortex (aPFC, BA 10) covaried with g , $r = .26$, and delay discounting, $r = -.40$, and partially mediated the relation between g and delay discounting. Overall, the results suggest that delay discounting is associated with intelligence in part due to processes instantiated in aPFC, a region known to support the integration of diverse information.

Keywords: delay discounting, temporal discounting, intertemporal choice, intelligence, working memory, cognitive ability, neuroeconomics, individual differences, anterior prefrontal cortex, frontopolar cortex

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Self-control is a critical human faculty that affects many spheres of life (e.g., Tangney *et al.*, 2004). One way of gauging self-control is by assessing individuals' tendencies to prefer smaller, more immediate rewards to larger, delayed rewards (e.g., Rachlin *et al.*, 1991). These delay discounting tasks measure self-control in a way that is relevant both to microeconomics, such as personal financial planning (Angeletos *et al.*, 2001), and to mental health, including substance abuse, attention deficit hyperactivity disorder, and problem gambling (for reviews, see Bickel & Marsch, 2001; Critchfield & Kollins, 2001). Nonetheless, the mechanistic bases of individual differences in delay discounting are largely unknown (but see Hariri *et al.*, 2006). Understanding the bases of such differences could potentially lead to interventions that can be used to enhance self-control (e.g., C. Blair & Razza, 2007).

In a recent meta-analysis, we found clear evidence for a negative relation between delay discounting and intelligence (Shamosh & Gray, in press). In 24 studies, nearly all found that preference for immediate rewards was associated with lower intelligence (IQ). The quantitative synthesis across 26 effect sizes revealed a small to moderate association (weighted mean $r = -.23$), establishing definitively that delay discounting and intelligence are negatively correlated. However, this review could not address the nature of the mechanisms supporting the relation.

One possibility is that individual differences in working memory account for the relation between delay discounting and intelligence. Working memory (WM) is the ability to maintain active representations of goal-relevant information despite interference from competing or irrelevant information (cf. working memory capacity; Engle, 2002). WM is strongly related to general intelligence (g ; for a review, see Conway *et al.*, 2003), a latent variable that accounts for

the widely observed positive intercorrelation among cognitive test performance (e.g., Jensen, 1998). Although correlations between WM capacity and *g* are typically large and robust, the two constructs are not isomorphic (Ackerman *et al.*, 2005; Kane *et al.*, 2005). At the neural level, brain regions involved during WM overlap substantially with those that support fluid intelligence, the ability to reason and solve novel problems (Gray & Thompson, 2004; Kane & Engle, 2004).

WM may also be related to delay discounting. Imposing a WM load increases impulsive responding on delay discounting tasks (Hinson *et al.*, 2003), suggesting that performing these tasks requires WM (e.g., to maintain reward values actively as one manipulates and integrates diverse information in order to choose between the alternatives). Consistent with this interpretation, deficits in the executive functions of WM are associated with higher trait impulsiveness (Whitney *et al.*, 2004). Moreover, neural networks supporting working memory are activated while performing delay discounting tasks (e.g., McClure *et al.*, 2004; Monterosso *et al.*, 2006), as well as during other decision-making tasks that require incurring short-term losses to achieve long-term gains (e.g., Tanaka *et al.*, 2004; Yarkoni *et al.*, 2005).

The goal of the present research was to identify candidate neural mechanisms that account for the relation between intelligence and delay discounting, focusing especially on mechanisms involved in WM. We operationalized intelligence by combining two tests of fluid reasoning and two tests of crystallized knowledge to derive a measure of *g*, because the relation between intelligence and delay discounting holds across a diverse array of measures (Shamosh & Gray, in press). We operationalized WM as both a latent variable based on working memory span tasks, and performance on 3-back tasks. WM-related brain activity was assessed during the latter. We replicated the finding that delay discounting is negatively related to intelligence, and

also found that it is negatively related to WM, as expected. To identify brain regions responsible for individual differences in WM, we first identified candidate regions by testing for WM-related neural activity that covaried with task performance. We then tested these regions for correlations with both delay discounting and *g*. Finally, we used mediation analyses to test whether activity in the surviving candidate regions of interest plausibly contributed to the relation between delay discounting and intelligence.

Method

Participants and procedure

Participants were recruited from Washington University in St. Louis and the surrounding community. All participants gave informed consent and none had a history of neurological or psychiatric disorder. The experimental protocol was approved by the Washington University Medical Center Human Subjects Committee. Of participants with complete delay discounting data, we excluded one with 3-back task accuracy that was not above chance ($d' = 0.31$, 3.51 SDs below the mean), and one with the highest 3-back accuracy ($d' = 3.70$, 3.60 SDs above the mean) who was unduly influencing analyses (Cook's $d = .39$ when regressing delay discounting on d'). Participants completed the behavioral measures prior to scanning, and returned on a separate day for the fMRI testing session (final $n = 103$; 59 female; age range 18-40 years, mean = 22.9).

Measures

Delay discounting. We administered a delay discounting task (Rachlin *et al.*, 1991) in which participants make a series of hypothetical choices between two monetary rewards, one immediate and one delayed, in two conditions. In one condition, the delayed reward was always \$200, and in the other it was \$40,000. In the former, the amount of the immediate reward was decreased sequentially across items from \$200 to \$10 in increments of \$10. In the latter, the

range was from \$40,000 to \$2,000 in increments of \$2,000. For each of the two delayed reward amounts, participants made 20 choices corresponding to each immediate reward amount for seven different delay periods: one month, six months, one year, two years, three years, five years, and eight years. Delay discounting was taken as the area-under-the-curve because it has good psychometric properties (Myerson *et al.*, 2001). This method involves determining an individual's present value for the delayed option at each amount (i.e., the estimated indifference point between the immediate and delayed rewards), plotting the resulting function, and calculating the proportion of total area falling under the curve. The score for the two delayed reward amounts was averaged and subtracted from 1 so that higher values would correspond to greater discounting. These scores were highly reliable (split-half $r = .98$), and previous research has demonstrated that delay discounting is a stable trait (Ohmura *et al.*, 2006).

Intelligence. All participants completed the Raven Advanced Progressive Matrices, Set II (APM; Raven *et al.*, 1998) and the Cattell Culture Fair Intelligence Test (Cattell, 1973) to obtain standard measures of fluid intelligence. They also completed the Vocabulary subscale of the WAIS-R (Wechsler, 1997) and the National Adult Reading Test - Revised (J. R. Blair & Spreen, 1989) to assess crystallized intelligence. To obtain a measure of g , we computed the average of participants' standardized scores on the four psychometric tasks. Cronbach's α for the four tasks was .88. Factor analysis of the four measures (unrotated, PAF extraction) revealed that a single factor explained 73.7% of the total variance (the scree plot suggested that a second factor was unlikely) and that all variables loaded strongly and approximately equally on this factor (range: .79 to .84). (Operationalizing g as the first unrotated factor did not change any of our conclusions drawn below, and has the potential disadvantage of capitalizing on sampling variability.)

Working memory. As one measure of individual differences in WM, participants completed four WM span tasks, Operation, Symmetry, Rotation, and Reading Span (Conway *et al.*, 2003), which are all scored using the same metric (0 to 1). Confirmatory factor analysis showed that all four tasks had high loadings (range 0.81 to 0.86) on a single factor that accounted for 70.1% of the total variance. WM span was taken as the average score on all four measures.

In the fMRI scanner, participants performed a 3-back version of the N-back task, a standard WM paradigm that requires pressing one key if the item presented on the screen was identical to that presented N trials previously ($N = 3$ in our study), and another key if the item was different. Participants completed the 3-back task over six functional scanning runs (with the exception of two participants who completed four runs, and nine others who completed five runs). Each scanning run involved two blocks of 32 trials (64 total trials per functional run) lasting for 2 s each. We discarded the first three task trials of each block because no match was possible; thus 58 trials per functional run were eligible for analysis. Three runs had faces as stimuli and three had concrete nouns, with order counterbalanced across participants. Every run was preceded by a short video; four of these videos involved positive and negative emotion inductions, order counterbalanced; we do not focus on them in our analyses. 3-back performance was taken as the signal detection measure of accuracy, d' , averaged across runs. Cronbach's α for d' across the six runs was .84.

There was no speed-accuracy tradeoff, $r(101) = -0.004$, and no further effects of interest to report involving response times.

fMRI data acquisition

We used a 3 Tesla Allegra System (Siemens, Erlangen, Germany) to collect whole-brain images: T1-weighted MP-RAGE structural images (FOV = 256 mm; 256 x 256 matrix; 1.25 mm

thick axial slices), and T2* BOLD functional images (asymmetric spin-echo echo-planar sequence; TR = 2360 ms; TE = 25 ms; FOV = 256 mm; flip angle = 90°; matrix = 64 x 64; 4 mm thick axial slices). Each functional run comprised 149 sequential whole-brain volumes (32 contiguous slices, 4 x 4 mm in-plane resolution).

During each functional run, the inter-trial intervals were jittered across a range of 0 to 4720 msec (0 to 2 TRs) in steps of 2360 msec (1 TR). Each task block was preceded and followed by a resting fixation block of 35 seconds. Additionally, each scanning run began with an unanalyzed 4 TR fixation period that allowed the scanner to reach steady state.

fMRI data analysis

Data were analyzed using Statistical Parametric Mapping 2 (SPM2) software (<http://www.fil.ion.ucl.ac.uk/spm>). Each functional run was preprocessed prior to analysis. Data were realigned using INRIAAlign (<http://www-sop.inria.fr/epidaure/Collaborations/IRMf/INRIAAlign.html>) to correct for movement. Images were normalized to Montreal Neurological Institute stereotaxic space using a 12-parameter affine transformation followed by nonlinear warping using basis functions, resampled into 3 mm isotropic voxels, and smoothed using an 8 mm full-width at half-maximum Gaussian kernel.

For each participant, we computed a basic contrast, task > fixation, across all six functional runs. Each 32-trial block of 3-back performance was modeled as a boxcar function convolved with a canonical hemodynamic response function. The magnitude of neural activity at each voxel was estimated using the general linear model. A contrast comparing task-related activity to fixation-related activity produced statistical parametric maps of the *t* statistic at each voxel for each subject. These maps were used in all subsequent fMRI analyses.

To identify WM-related neural mechanisms related to both delay discounting and g , we first isolated candidate regions of interest (ROIs) supporting WM-related processes. We operationalized this requirement as regions in which WM-related activity covaried with WM performance. We subjected each resulting ROI to three additional criteria to ascertain whether it likely contributed to the relation between g and delay discounting. Activity in the ROI had to correlate with both g and delay discounting, and statistically mediate the relation between them (with each analysis using a significance threshold of $p < .05$, Bonferroni corrected). (A similar analysis would have been to correlate delay discounting with WM-related activity, and then probe those regions using ROI analyses. Doing so is less straightforward conceptually, yet also identifies a left aPFC region very similar to that reported in Table 2.)

Accordingly, we first conducted a group-level random-effects analysis to identify regions in which activity during the 3-back task covaried with 3-back accuracy (as defined by 15 or more contiguous voxels in which task > fixation contrast values correlated with d' , $p < .001$, uncorrected). We defined these as ROIs (MarsBar toolbox, <http://marsbar.sourceforge.net>), and used t -tests to determine the extent to which the region was related to delay discounting and g (Table 2). At a group level, performing the 3-back task was associated with activation or deactivation in some but not all of the ROIs. The mean percent signal change for each individual in each ROI was computed from task-related activity (mean B values across all voxels in the ROI) and global signal (mean across all voxels). These values were used to perform correlations with behavioral measures (d' , g) and mediation tests using the bootstrap method to test significance of indirect effects (bias-corrected confidence interval method, bootstrap $N = 2000$; Shrout & Bolger, 2002). In an imaging context, mediation analyses can be used to test whether a given region can plausibly account for the covariation between two behavioral variables, thereby

implicating the region in supporting a complex function (cf. Gray Chabris, & Braver, 2003). In the present study, a significant mediation effect indicates that WM-related brain activity is likely to be responsible, at least in part, for the observed relation between *g* and delay discounting.

Results

Behavioral findings

Table 1 presents descriptive statistics and correlations between measures. As expected, WM was strongly related to *g*. The two WM measures (*d'*, span) were highly correlated, indicating good convergent validity. As expected, delay discounting was negatively correlated with *g* (i.e., greater self-control was associated with higher intelligence). Delay discounting was also negatively correlated with both measures of WM to similar degrees.

When delay discounting was regressed on WM span and *g* simultaneously, the association between WM span and delay discounting was not significant ($\beta = .02, p = .87$), whereas the relation between *g* and delay discounting remained strong ($\beta = -.41, p < .001$), $F_{(2, 100)} = 9.55, p < .001, R^2 = .16$. This R^2 value was effectively identical to that for *g* alone, indicating that WM span did not account for additional variability in delay discounting above and beyond *g*, $R^2_{\text{change}} = .00$.

The same conceptual analysis with *d'* instead of WM span yielded virtually identical conclusions. When delay discounting was regressed on *d'* and *g* simultaneously, the association between *d'* and delay discounting was eliminated ($\beta = -.01, p = .95$), whereas the relation between *g* and delay discounting remained robust ($\beta = -.40, p < .001$), $F_{(2, 100)} = 9.54, p < .001, R^2 = .16$. Again, this R^2 value was effectively identical to that for *g* alone, indicating that *d'* did not account for additional variability in delay discounting above and beyond *g*, $R^2_{\text{change}} = .00$.

The behavioral findings suggest that g is related to delay discounting in part due to processes or mechanisms common to g and WM (approximately 35% of the variance). There was effectively no unique contribution of WM alone to delay discounting (beyond WM processes that contribute to g), so WM mechanisms that relate to delay discounting are shared by g . To provide further constraints on the nature of these shared mechanisms, we used WM-related neural activity to identify brain regions plausibly supporting the relation between g and delay discounting.

fMRI findings

Following the rationale elaborated above, we first identified candidate neural regions that plausibly supported individual differences in WM performance. Across the whole brain, variation in 3-back task accuracy (d') covaried with task-related activity in six ROIs (Table 2), positively or negatively depending on the region. A similar pattern held for the relation between g and WM-related neural activity in all six regions. Delay discounting was only reliably correlated with WM-related activity in 3 regions.

After Bonferroni correction for six comparisons, three ROIs showed significant associations with delay discounting. The strongest association ($r = -.40$) was in a region of left anterior prefrontal cortex (aPFC; lateral frontopolar cortex, BA 10; Figure 1). Unlike most of the ROIs, this region did not show group level WM-related activation or deactivation (despite greater activity being associated with better WM performance; Table 2).

As a final test of whether each candidate region plausibly supported the relation between g and delay discounting, we conducted mediation analyses. Of the six ROIs, left aPFC was the only one to remain a significant mediator after correction for multiple comparisons (Table 2).

For left aPFC, the indirect effect of *g* on delay discounting was significant, and the direct effect of *g* on delay discounting also remained significant, indicating partial mediation (Figure 1B).

Discussion

The present study is the first, to our knowledge, to investigate and identify neural mechanisms that account for the relation between intelligence and individual differences in delay discounting. We replicated our meta-analytic finding that delay discounting is negatively related to intelligence (Shamosh & Gray, in press), and also found that delay discounting covaried negatively with WM, especially WM processes shared with intelligence. Additionally, individual differences in left aPFC partially explained the tendency of more intelligent individuals to resist smaller, sooner rewards. Across 103 subjects, neural activity in aPFC during a difficult working memory task was positively associated with WM accuracy and intelligence, and negatively associated with delay discounting. A path analysis showed that this neural activity partially mediated the association between *g* and delay discounting (and between WM and delay discounting). In a neuroimaging context, this mediation indicates that the WM-related function of this brain region accounts for some of the covariation between *g* and delay discounting. This finding is consistent with the overlapping neural substrates of *g* and WM (Gray & Thompson, 2004; Kane & Engle, 2004) and suggests that these substrates also overlap with those of delay discounting.

Our findings suggest that the link between *g* and delay discounting is supported in part by aPFC. In our data, aPFC activity is associated with better WM performance, higher intelligence, and reduced delay discounting. Interestingly, activity in this region may improve WM without being essential for it, because group-mean activity was not reliably different from zero despite a significant association with better WM performance across individuals. However, this

interpretation depends on aPFC activity in the baseline condition, and some meta-analyses have found aPFC to be engaged during N-back tasks (e.g., Owen *et al.*, 2005). Our results, in conjunction with previous research, suggest that its function may be flexibly involved in various forms of higher cognition. The left aPFC ROI falls within a brain region that has been implicated in a wide range of cognitive processes (for a review, see Gilbert *et al.*, 2006), which is noteworthy in part because *g* reflects the common variance among diverse abilities. Also notable is that this region is among those in which cortical development tracks with maturation of intelligence in children (Shaw *et al.*, 2006). According to a unifying theory of aPFC function that may explain its flexibility (Koechlin & Hyafil, 2007; Ramnani & Owen, 2004), the region's principal role is to integrate the products of multiple, concurrent subtasks promoting a superordinate behavioral goal, especially when these products are abstract or complex. Given this interpretation, it is not surprising that, in our study, better performance on the WM task (3-back) tracked with greater recruitment of this region: ramping up this integrative machinery could facilitate coping with any number of the task's demanding attributes (e.g., integrating target decision-making with the updating of WM content following presentation of each item).

The association of aPFC activity with delay discounting and intelligence in addition to WM performance is consistent with several neuroimaging studies implicating left lateral aPFC in integration as distinct from other processes more specifically associated with working memory, such as maintenance and manipulation of information. We recently found, for example, that activity in left lateral aPFC associated with abstract, relational integration varies independently of other working memory demands in analogical reasoning (Green *et al.*, 2006). Left lateral aPFC appears to play a similar selective role in integration during mathematical problem solving (De Pisapia *et al.*, 2007), matrix reasoning (Christoff *et al.*, 2001), and episodic memory

(Reynolds *et al.*, 2006). In view of these converging results, the present finding has several implications regarding the nature of delay discounting and individual differences on this measure. It is consistent with the abstract nature of the goals and component arguments (e.g., future selves, reward events, delay periods) represented during the calculation of delay discounting. Moreover, it suggests that variability in delay discounting hinges on individual differences in the ability to successfully integrate these abstract goals and component arguments.

The specific role of integration in delay discounting could play out in a number of possible ways. Delay discounting tasks appear to recruit two distinct neural systems, one limbic and one prefrontal (McClure *et al.*, 2004), and differences in aPFC function could impact the way in which signals from these systems are combined. Delay discounting tasks may also involve the integration of cognitive and affective processes (Gray *et al.*, 2002), or still yet other processes, such as reasoning about present and future selves (Frederick, 2006), evaluating abstract and concrete features of the imagined event of receiving the rewards (Trope & Liberman, 2003), and maintaining information about previous options and choices in order to achieve temporally consistent behavior (Yarkoni *et al.* 2005). Whatever the specific role of integration in delay discounting, more intelligent individuals may discount less in part either because they are better at integration or because they adopt more integration-intensive strategies on delay discounting tasks (cf. Frederick, 2005).

The present study raises some additional questions for future research. Firstly, mediation of the relation between *g* and delay discounting by WM-related mechanisms was only partial, meaning that other mechanisms also contribute to the association between *g* and delay discounting. This suggestion is also consistent with our behavioral finding that *g* accounted for variance in delay discounting independently from WM. Other mechanisms through which

intelligence relates to delay discounting remain to be investigated. Secondly, other regions besides aPFC demonstrated WM-related activity that was correlated with delay discounting. Although the correlations were substantially weaker and failed to mediate the relation between g and delay discounting, investigating their possible role in delay discounting is worthwhile, especially given that previous studies (e.g., McClure *et al.*, 2004) have implicated some of them directly as being involved during delay discounting tasks.

In summary, we found that WM-related activity in a region of left lateral frontopolar aPFC partially mediated the relation between g and delay discounting. Because g and WM are closely related behaviorally and neurally (Gray & Thompson, 2004), and because WM did not predict delay discounting independently of g at the behavioral level, this region likely supports processes through which WM and g jointly relate to delay discounting. Based on previous work, this region of aPFC probably supports abstract, relational integration, a process that may be critically involved in intertemporal choice and other demanding tasks. Thus, individuals with higher intelligence may prefer larger, later rewards to smaller, sooner ones primarily because they are better at these integrative processes, or because they are more likely to use them.

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Table 1. Correlations between behavioral measures.

	1	2	3	4	5	6	7	8
1 <i>g</i>	-							
2 Raven APM	0.88	-						
3 Cattell Culture Fair	0.90	0.76	-					
4 WAIS Vocabulary	0.70	0.59	0.62	-				
5 NART-R	0.46	0.58	0.56	0.79	-			
6 WM (<i>d'</i>)	0.60	0.59	0.60	0.44	0.42	-		
7 WM span	0.58	0.58	0.63	0.45	0.47	0.55	-	
8 Delay discounting	-0.40	-0.37	-0.31	-0.41	-0.28	-0.25	-0.22	-
Mean	0.00	25.08	29.36	48.60	20.74	1.98	0.70	0.43
Standard deviation	0.51	6.09	5.46	8.83	8.74	0.48	0.13	0.20

Note. See text (Methods) for a description of measures. All correlations are significant with $n = 103$ at $p < .025$ (two-tailed), $p_{\text{rep}} = .92$.

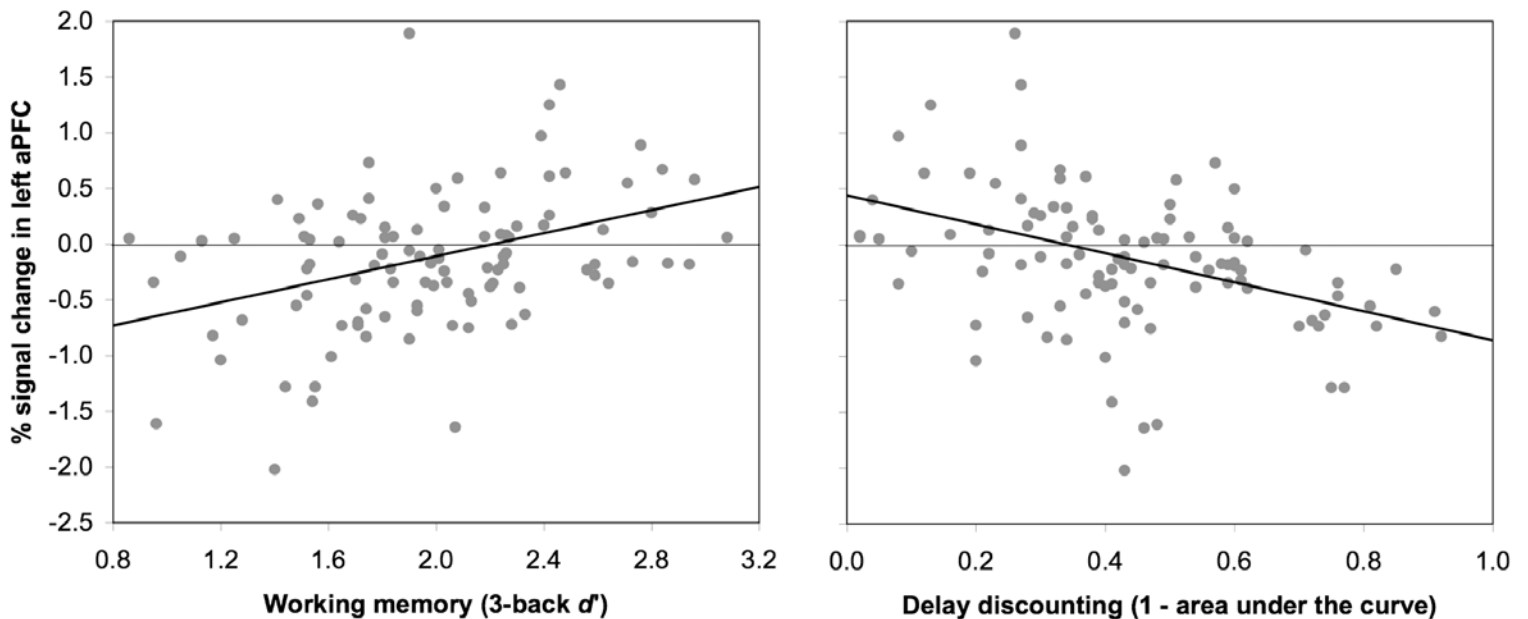
Table 2. Regions of interest and relation to behavioral variables.

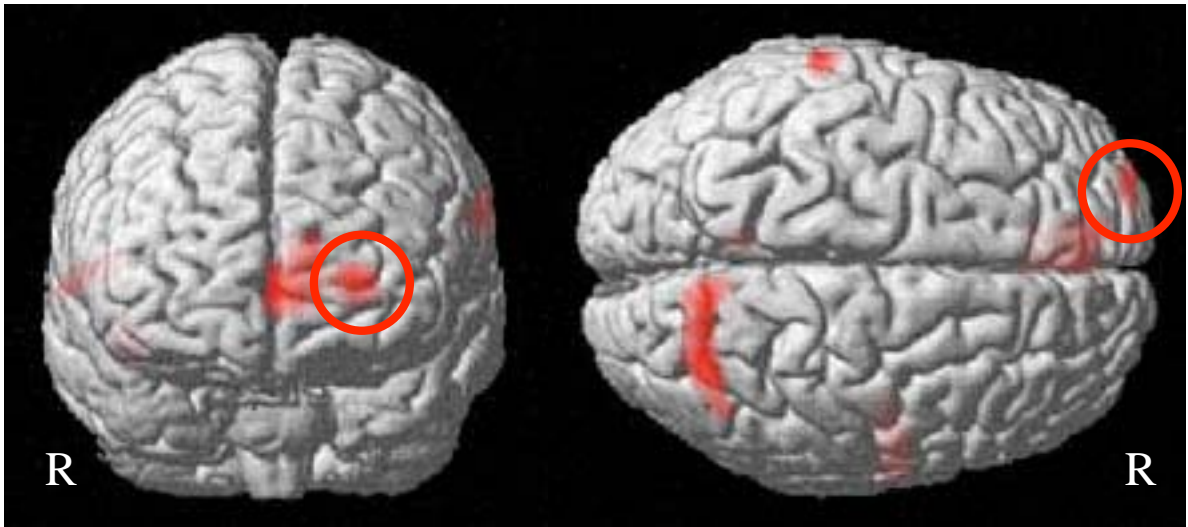
Region	Coordinates			Cluster extent	Correlations, $r(101)$			3-back > fixation	Mediation indirect path β (SE)	
	x	y	z		WM d'	g	Delay Discounting	$t(102)$	$d' \rightarrow DD$	$g \rightarrow DD$
L middle frontal gyrus (BA 10; aPFC)	-22	61	8	17	0.37*	0.26*	-0.40*	-2.23	-0.13* (0.04)	-0.08* (0.03)
L anterior cingulate (BA 32)	-3	40	7	145	-0.38*	-0.37*	0.28*	-9.07*	-0.08 (0.05)	-0.06 (0.05)
L inferior parietal lobule (BA 40)	-59	-32	22	24	-0.36*	-0.30*	0.23	-0.64	-0.06 (0.05)	-0.04 (0.03)
R precuneus (BA 7)	10	-70	54	65	0.44*	0.26*	-0.17	13.19*	-0.03 (0.04)	-0.02 (0.02)
R temporal (BA 21)	39	-9	-11	86	-0.36*	-0.27*	0.27*	-2.88*	-0.08 (0.05)	-0.05 (0.03)
L posterior cingulate gyrus (BA 30)	-9	-62	12	17	-0.34*	-0.29*	0.23	-9.88*	-0.06 (0.04)	-0.04 (0.03)

Note. Regions are correlated with activity during the 3-back task at $p < .001$ (uncorrected), cluster extent threshold ≥ 15 voxels. * $p < .0083$ ($p < .05$, Bonferroni corrected for six ROIs); $p_{\text{rep}} > .955$

Figure 1. A) Association between activity in the left anterior prefrontal cortex (aPFC) region of interest and both delay discounting and working memory (d'). B) Bivariate correlations between 3-back activity and 3-back performance (red), $p < .001$, uncorrected, cluster extent threshold ≥ 15 voxels ($p_{\text{corrected}} < .05$). Left anterior prefrontal region of interest is circled. C) Activity in left lateral anterior prefrontal cortex (aPFC) partially mediates the relation between intelligence (g) and delay discounting. Values adjacent to arrows represent standardized regression coefficients. Bootstrapped 95% confidence intervals (bias-corrected percentile method) are provided within parentheses. * $p < .0083$, $p_{\text{rep}} > .955$; ** $p < .001$, $p_{\text{rep}} = .99$.

A.





C.

