Evidence for absence of links between striatal dopamine synthesis capacity and working memory capacity, spontaneous eye-blink rate, and trait impulsivity

Ruben van den Bosch[1], Frank H. Hezemans[1], Jessica I. Määttä[2], Lieke Hofmans[3], Danae Papadopetraki[1,4], Robbert-Jan Verkes[4], Andre F. Marquand[1,4], Jan Booij[5,6], Roshan Cools[1,4]

1. Radboud University, Donders Institute for Brain, Cognition and Behaviour, Nijmegen, The Netherlands
2. Department of Clinical Neuroscience, Karolinska Institutet, Stockholm, Sweden
3. Department of Developmental Psychology, University of Amsterdam, The Netherlands
4. Radboud University Medical Center, Department of Psychiatry, Donders Institute for Brain, Cognition and Behaviour, Nijmegen, The Netherlands
5. Department of Radiology and Nuclear Medicine, Amsterdam University Medical Centers, location University of Amsterdam, The Netherlands
6. Radboud University Medical Center, Department of Medical Imaging, Nijmegen, The Netherlands

Abstract

Individual differences in striatal dopamine synthesis capacity have been associated with working memory capacity, trait impulsivity and spontaneous eye-blink rate (sEBR), as measured with readily available and easily administered, 'off-the-shelf' tests. Such findings have raised the suggestion that individual variation in dopamine synthesis capacity, estimated with expensive and invasive brain positron emission tomography (PET) scans, can be approximated with simple, more pragmatic tests. However, direct evidence for the relationship between these simple trait measures and striatal dopamine synthesis capacity has been limited and inconclusive. We measured striatal dopamine synthesis capacity using [^{18}F]-FDOPA PET in a large sample of healthy volunteers (N=94) and assessed the correlation with simple, short tests of working memory capacity, trait impulsivity, and sEBR. We additionally explored the relationship with an index of subjective reward sensitivity. None of these trait measures correlated significantly with striatal dopamine synthesis capacity, nor did they have out-of-sample predictive power. Bayes Factor analyses indicated the evidence was in favour of absence of correlations for all but subjective reward sensitivity. These results warrant caution for using these off-the-shelf trait measures as proxies of striatal dopamine synthesis capacity.

Introduction

The mesocorticolimbic dopamine system plays a key role in a range of cognitive functions, and individual differences in dopamine function have been associated with various behavioural and physiological trait characteristics, including working memory, impulsivity, and spontaneous eye-blink rate (sEBR). For example, evidence from work with brain positron emission tomography (PET) in humans indicates that working memory capacity is positively associated with both striatal dopamine synthesis capacity, assessed with 6-[^{18}F]fluoro-l-m-tyrosine ([^{18}F]-FMT) PET imaging, and striatal dopamine release, estimated with [^{11}C]-Raclopride PET imaging (Bäckman et al., 2011; Clatworthy et al., 2009; Cools et al., 2008; Garrett et al., 2022; Landau et al., 2009; Salami et al., 2019; but see Braskie et al., 2008, 2011; Klostermann et al., 2012). Furthermore, genetic variation in striatal dopamine function has been linked to working memory performance (Frank and Fossella, 2011), unmedicated patients with Parkinson's disease show striatal underactivation and impaired performance during working memory updating (Marklund et al., 2009), and direct dopamine measurements and manipulations in animal models have also linked striatal dopamine to working memory performance (Collins et al., 2000; Kellendonk et al., 2006).

In line with a link between working memory and impulsivity (Cools et al., 2007; James et al., 2007), work with PET imaging in human volunteers has also demonstrated a positive correlation between impulsivity and both striatal dopamine release and synthesis capacity as well as striatal dopamine D_2-receptor availability (Buckholtz et al., 2010; Kim et al., 2014; van Holst et al., 2018). This is supported by evidence from animal studies indicating that impulsivity is linked to dopamine D_2-receptor availability and dopamine levels in the ventral striatum (Dalley et al., 2007; Martinez et al., 2020). Such findings provide a neural mechanistic account of key links between working memory and impulsivity (Cools et al., 2007; James et al., 2007), as well as working memory and impulse control deficits in disorders that implicate abnormal dopamine signaling, such as schizophrenia (Barch and Ceaser, 2012), drug addiction (Jentsch and Taylor, 1999) and Parkinson's disease (Cools et al., 2022).

Intriguingly, some of the cognitive factors associated with dopamine transmission have been shown to be captured by sEBR, with sEBR correlating with working memory task performance (Ortega et al., 2022), attentional load and fatigue (Maffei and Angrilli, 2018), attentional control (Colzato et al., 2009; Unsworth et al., 2019), working memory updating and gating (Rac-Lubashevsky et al., 2017), and exploration during reinforcement learning (Van Slooten et al., 2019). In addition, in line with findings that sEBR can explain dopaminergic drug effects (e.g. Cavanagh et al., 2014), it has been argued that sEBR is an effective measure of striatal dopamine activity (Jongkees and Colzato, 2016), as suggested by positive correlations with dopamine D_2-receptor availability (Groman et al., 2014; but

see Dang et al., 2017), as well as post-mortem dopamine concentrations in the caudate nucleus of monkeys (Taylor et al., 1999).

Findings like these have raised the suggestion that instead of requiring invasive and expensive brain PET imaging, we can approximate striatal dopamine activity with relatively simple, off-the-shelf tests, for example the digit span or listening span tests of working memory capacity (Cools et al., 2008; Landau et al., 2009), eye-blink rate measurements at rest (Jongkees and Colzato, 2016), or self-report measures of relevant traits such as impulsivity or reward sensitivity (Buckholtz et al., 2010; Clatworthy et al., 2009; Depue and Collins, 1999; Froböse et al., 2018). If this were true, then this would have great implications for a variety of disciplines, including clinical and cognitive psychology, neuroscience, and experimental medicine. After all, it would mean that inexpensive and noninvasive, off-the-shelf tests could be used as proxy measures for studying individual differences in dopamine function and for stratifying dopaminergic drug effects by baseline dopamine levels. Indeed, we and others have interpreted a variety of working memory span-, sEBR- and impulsivity-dependent changes in behaviour (for example elicited by drug administration) as reflecting individual variation in baseline dopamine function (Cavanagh et al., 2014; Clatworthy et al., 2009; Colzato et al., 2008; Cools et al., 2007; Frank and O'Reilly, 2006; Froböse et al., 2018; Kandroodi et al., 2021; Kimberg et al., 1997; Slagter et al., 2015; Swart et al., 2017; van der Schaaf et al., 2014).

So far, however, the predictive value of working memory capacity, trait impulsivity and sEBR for individual variation in dopamine function in the human brain has not yet been established. This requires assessing the relationships of these measures with dopamine function measured with PET imaging in studies with much larger sample sizes than used so far, as well as testing the predictive accuracy of the putative proxy measures for previously unseen data (Yarkoni and Westfall, 2017). In fact, sample sizes of prior studies of these measures have been so small that they might well have produced inflated and unstable estimates of the correlation coefficient (Loken and Gelman, 2017; Marek et al., 2022; Schönbrodt and Perugini, 2013). For example, although both Cools et al. (2008) and Landau et al. (2009) (N=11 and N=22, respectively) reported a positive correlation between working memory capacity, measured with the listening span, and dopamine synthesis capacity, subsequent studies using a partly overlapping sample did not find this relationship (Braskie et al., 2011, 2008; Klostermann et al., 2012). Furthermore, trait impulsivity has also been observed to correlate negatively rather than positively with dopamine synthesis capacity (Petzold et al., 2019; Smith et al., 2015), and Sescousse et al. (2018) reported evidence for the absence of a correlation between sEBR and striatal dopamine synthesis capacity, similar to the lack of a correlation between sEBR and dopamine D_2-receptor availability observed by Dang et al. (2017).

Here, we measured striatal dopamine synthesis capacity with [^{18}F]-FDOPA PET imaging in a much larger sample of healthy volunteers (N=94) to establish the predictive link with three commonly used putative proxy measures of dopamine: working memory capacity, trait impulsivity, and sEBR. In addition, we explored the potential correlation between dopamine synthesis capacity and a questionnaire index of subjective reward sensitivity, a process that is intimately linked with dopamine function (Costumero et al., 2013; Depue and Collins, 1999; Locke and Braver, 2008). We tested the hypothesis that these trait measures were positively correlated with, and predictive of, estimates of striatal dopamine synthesis capacity.

Results

Absence of correlations between trait measures and striatal dopamine synthesis capacity

First, we report the Pearson correlations between striatal dopamine synthesis capacity and working memory capacity, trait impulsivity, sEBR and subjective reward sensitivity. Dopamine synthesis capacity was quantified as the [^{18}F]-FDOPA influx rate (k_i^{cer}) for three striatal regions of interest (ROIs) based on a functional parcellation of the striatum (Piray et al., 2017): the caudate nucleus, putamen and nucleus accumbens (ventral striatum). Working memory capacity was indexed with the Digit Span test (Groth-Marnat, 1997) and Listening Span test (Daneman and Carpenter, 1980); trait impulsivity was assessed with the Barratt Impulsiveness Scale (BIS-11; Patton et al., 1995); subjective reward sensitivity was assessed using the Behavioural Activation Scale (BAS; Carver and White, 1994); and sEBR was calculated from electro-oculography recordings (see Methods for details). For trait measures that resulted in multiple (sub)scores, we used the total or composite score as the putative proxy measure. We report additional correlation analyses exploring the relationships between subscales of the trait measures and dopamine synthesis capacity in the Supplementary Information.

There were no significant correlations between dopamine synthesis capacity, in any of the three striatal ROIs, and working memory capacity, trait impulsivity, or sEBR, even without correcting for multiple comparisons (Figure 1; Table 1; all uncorrected p-values > 0.050, all corrected p-values ≥ 0.365). There was also no significant correlation with subjective reward sensitivity after correction for multiple comparisons (Figure 1; Table 1; corrected p-values = 0.127). Specifically, the coefficients of correlation between dopamine synthesis capacity and both the Digit Span and Listening Span were almost zero in all three ROIs (Figure 1a-b; Table 1). In fact, the direction of the association between Digit Span and dopamine synthesis capacity was negative (e.g. ρ = -0.071 for the nucleus accumbens). The coefficient of the correlation between trait impulsivity and dopamine synthesis capacity

was also almost zero in all three ROIs, and the direction of the association was, if anything, negative (Figure 1c; Table 1). There were also no significant correlations between sEBR and dopamine synthesis capacity (Figure 1d; Table 1), with correlation coefficients of almost zero in the caudate nucleus and putamen, and a positive (but non-significant) association in the nucleus accumbens (ρ = 0.123). That association was slightly stronger but still not significant after correction for multiple comparisons when excluding 9 participants that received inconsistent instructions for the sEBR measurement (see Methods; ρ = 0.184, adjusted p-value = 0.143). Among the four trait measures under consideration, subjective reward sensitivity was most strongly and positively associated with dopamine synthesis capacity (e.g. ρ = 0.179 in the nucleus accumbens), but again the correlations were not statistically significant (Figure 1e; Table 1).

In accordance with the ROI-based correlation analyses, voxel-wise regression analyses of the trait measures on the dopamine synthesis capacity PET data did not reveal any significant clusters, and the location of any sub-threshold clusters were generally consistent with the ROI-based results (Figure 2).
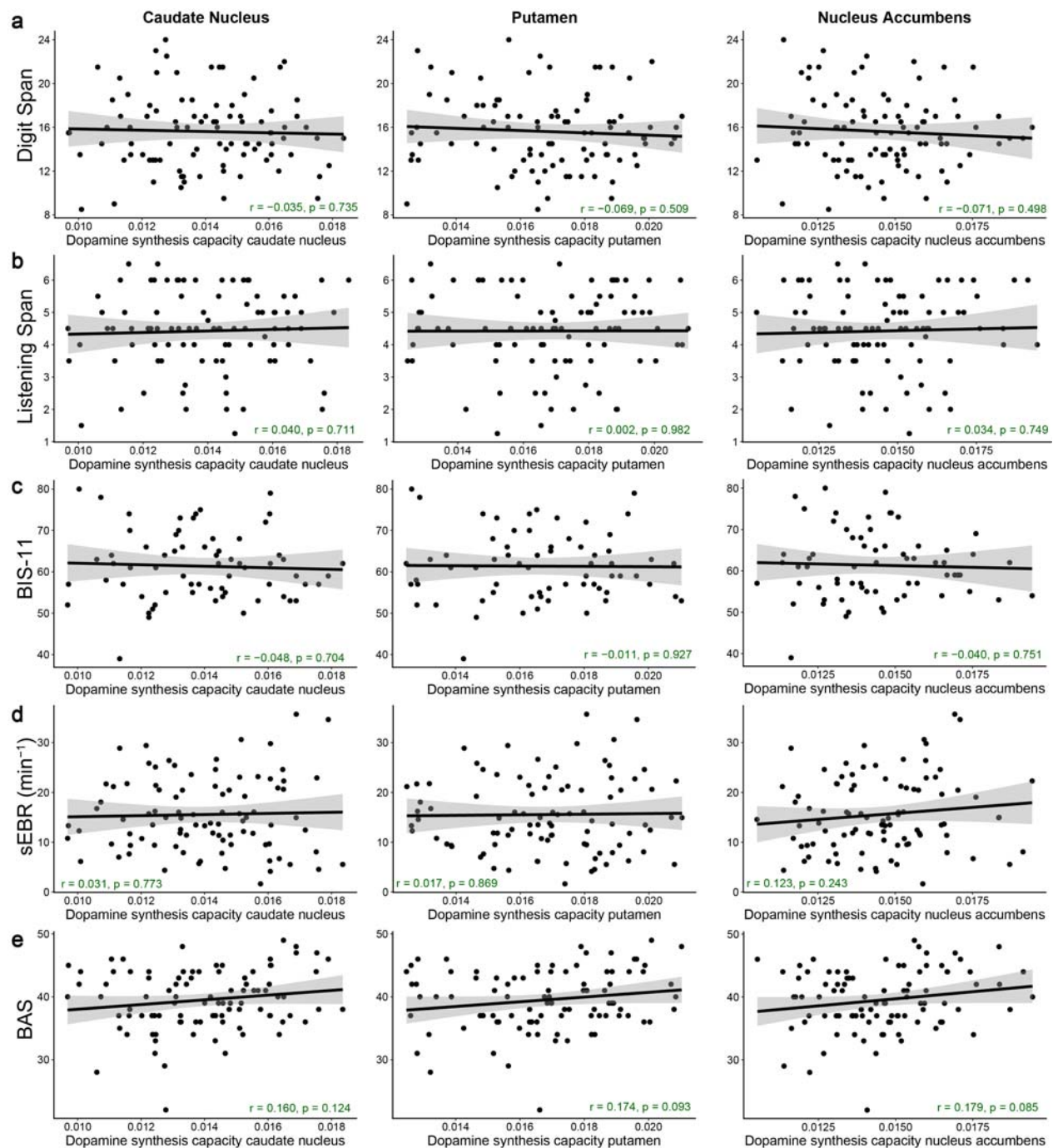
Figure 1. No significant correlations between striatal dopamine synthesis capacity and working memory capacity, trait impulsivity, spontaneous eye-blink rate, or subjective reward sensitivity. *Pearson correlations between dopamine synthesis capacity (k_i^{cer}) in the caudate nucleus, putamen or nucleus accumbens ROIs and **(a)** working memory capacity measured with the Digit Span task (N = 94), **(b)** working memory capacity measured with the Listening Span task (N = 94), **(c)** trait impulsivity measured with the BIS-11 questionnaire (N = 66), **(d)** spontaneous eye-blink rate (N = 92), or **(e)** subjective reward sensitivity measured with the Behavioural Activation Scale (N = 94). The p-values provided in the annotations are not corrected for multiple comparisons.*

Table 1. Statistics of the Pearson correlation analyses between striatal dopamine synthesis capacity and working memory capacity, trait impulsivity, spontaneous eye-blink rate, and subjective reward sensitivity.

Trait measure	Striatal ROI	ρ	p-value	adjusted p-value	BF_{01} (0,1)	BF_{01} (-1,1)
Digit Span	caudate nucleus	-0.035	0.632	1	9.93	7.33
	putamen	-0.069	0.746	1	12.19	6.25
	nucleus accumbens	-0.071	0.751	1	12.31	6.19
Listening Span	caudate nucleus	0.04	0.355	1	5.52	7.09
	putamen	0.002	0.491	1	7.45	7.59
	nucleus accumbens	0.034	0.375	1	5.78	7.22
BIS-11	caudate nucleus	-0.048	0.648	1	8.56	6.06
	putamen	-0.011	0.536	1	6.98	6.48
	nucleus accumbens	-0.04	0.625	1	4.97	6.19
sEBR	caudate nucleus	0.031	0.386	0.773	6.01	7.36
	putamen	0.017	0.434	0.773	6.7	7.57
	nucleus accumbens	0.123	0.122	0.365	2.24	3.92
BAS	caudate nucleus	0.16	0.062	0.127	1.3	2.42
	putamen	0.174	0.046	0.127	1.02	1.93
	nucleus accumbens	0.179	0.042	0.127	0.94	1.8

ρ: Pearson correlation coefficient; corresponding one-sided p-values (for a positive association) are reported both with and without Holm-Bonferroni correction for multiple comparisons for three striatal ROIs; BF_{01} (0,1): Bayes Factor for the evidence in favor of the null hypothesis of no positive correlation (H0) versus the alternative hypothesis of a positive correlation (H1); BF_{01} (-1,1): Bayes Factor for the non-directional hypotheses quantifying the evidence in favour of the null hypothesis of no correlation (H0) versus the alternative hypothesis that there is a correlation (H1); BIS-11: Barratt Impulsiveness Scale, assessing trait impulsivity; sEBR: spontaneous eye-blink rate; BAS: Behavioural Activation Scale, assessing subjective reward sensitivity.
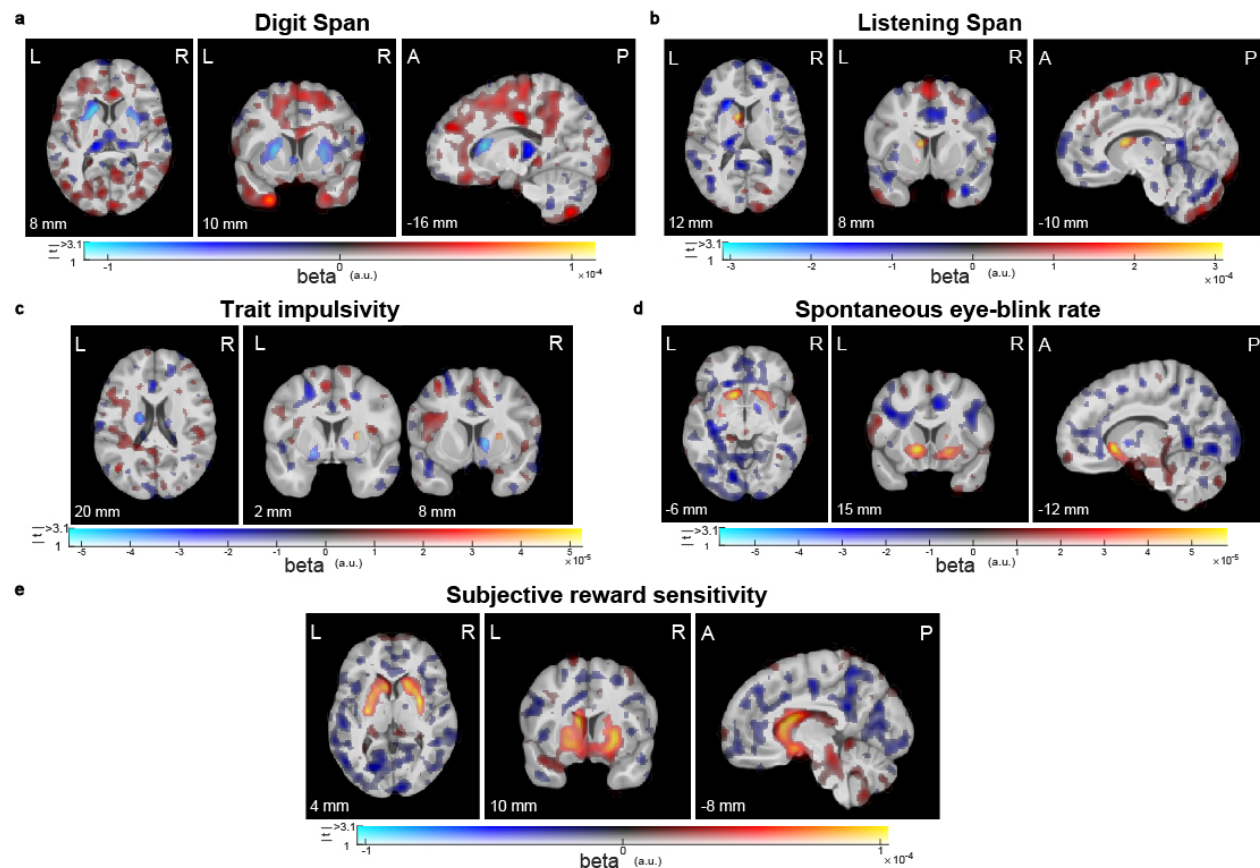
Figure 2. Visualization of sub-threshold correlations between striatal dopamine synthesis capacity and working memory capacity, trait impulsivity, spontaneous eye-blink rate, or subjective reward sensitivity. *Results from voxel-wise regression analysis of the trait measures onto the PET index of dopamine synthesis capacity for **(a)** working memory capacity measured with the Digit Span task (N = 94), **(b)** working memory capacity measured with the Listening Span task (N = 94), **(c)** trait impulsivity measured with the BIS-11 questionnaire (N = 66), **(d)** spontaneous eye-blink rate (N = 92), or **(e)** subjective reward sensitivity measured with the Behavioural Activation Scale (N = 94). In these dual-coded images, colour indicates the size of the contrast estimate and the opacity represents the t-values. Voxels with t-values above the threshold of p < 0.001, uncorrected, are fully opaque. There are no significant clusters in these images (peak-level family-wise error correction at p < 0.05 after small-volume correction for the combination of the caudate nucleus, putamen and nucleus accumbens). Any significant clusters would have been encircled in black for red blobs or white for blue blobs. The results are overlaid on the group-average T1-weighted anatomical MRI scan in MNI152 coordinate space. This visualization approach was introduced by Allen et al. (2012) and implemented by Zandbelt (2017).*

Because of the lack of statistically significant correlations, we sought to quantify the evidence in our data for the absence of correlations between the trait measures and dopamine synthesis capacity, using a Bayesian analysis of the associations. We calculated the Bayes Factors (BF_{01}) of the null hypotheses that dopamine synthesis capacity values and the different trait measures are not positively correlated (H0) versus the alternative hypotheses that they are positively correlated (H1; Table 2). For working memory capacity, the BF_{01} results indicated that the data were approximately 10-12 times more likely under the null hypothesis of no positive correlation than under the alternative hypothesis of a

positive correlation for the Digit Span, and approximately 6 times more likely under the null hypothesis for the Listening Span, thus providing strong evidence for H0 over H1 for the Digit Span and moderate evidence for the Listening Span. Similarly, there was strong evidence for the null hypothesis of no positive correlation between trait impulsivity and dopamine synthesis capacity ($BF_{01} \approx$ 5-8). For sEBR, the analysis revealed moderate evidence for the null hypothesis of no positive correlation with dopamine synthesis capacity in the caudate nucleus and putamen ($BF_{01} \approx$ 6), but only weak, inconclusive evidence in the nucleus accumbens ($BF_{01} \approx$ 2). The data for the correlation between subjective reward sensitivity and dopamine synthesis capacity were equally likely under H0 or H1 ($BF_{01} \approx$ 1), indicating that the Bayesian analysis was inconclusive about the evidence for the existence of a positive correlation.

To assess the sensitivity of the Bayes Factors to the priors that were used in the analyses, we performed a Bayes Factor robustness check. This analysis indicated that the above conclusions hold even when specifying strong prior beliefs in the existence of positive correlations (Supplementary Figure 2).

We also assessed Bayes Factors quantifying the relative evidence for the non-directional hypotheses of no correlation (H0) versus a (positive or negative) correlation (H1) between the trait measures and dopamine synthesis capacity (Table 2). This revealed moderate evidence for the null hypothesis of no correlation (H0) between striatal dopamine synthesis capacity and working memory capacity ($BF_{01} \approx$ 5-7), trait impulsivity ($BF_{01} \approx$ 6), or sEBR ($BF_{01} \approx$ 4-8). For subjective reward sensitivity the relative evidence for the null hypothesis remained inconclusive ($BF_{01} \approx$ 2).

Of note, previous studies that used smaller sample sizes typically reported much larger correlation coefficients than those observed in the current study (Figure 1; Table 1; range: -0.071 – 0.179). One potential explanation for this apparent contradiction is sampling variability: The estimates of effect size can be inflated due to chance with small samples and increasingly large samples are needed to sufficiently reduce estimated standard errors to detect smaller effects (Marek et al., 2022; Schönbrodt and Perugini, 2013). To address this issue, we repeatedly sampled (with replacement) random subsets of varying sizes from our full dataset. For each of those random subsets, we estimated the correlation coefficients between each trait measure and striatal dopamine synthesis capacity, so that we could examine the sampling variability of the correlation coefficient as a function of sample size. As expected, this analysis revealed substantial sampling variability at smaller sample sizes, such that two independent population subsamples could produce opposite conclusions about the same correlation. For example, at N=15, the 95% confidence interval for the correlation between sEBR and dopamine synthesis capacity in the nucleus accumbens was [-0.42, 0.62], highlighting how such correlations can be strongly

influenced by chance. The Supplementary Figure 6 illustrates the sampling variability by sample size for all trait measures and striatal ROIs.

Trait measures fail to predict striatal dopamine synthesis capacity

The statistical significance of a correlational model evaluated 'in-sample' does not necessarily speak to that model's predictive accuracy for previously unseen data (Yarkoni and Westfall, 2017). We therefore used resampling methods, specifically k-fold cross-validation (k=10 with 100 repeats) and permutation testing, to estimate to what extent each of the trait measures could predict striatal dopamine synthesis capacity, using simple linear regression models (see Methods for details). We indexed predictive accuracy with the out-of-sample coefficient of determination (R^2), and provide the root mean square error (RMSE) as an additional performance measure (Table 2).

For all trait measures, the cross-validated R^2 was negative for dopamine synthesis capacity in the caudate nucleus, putamen, and nucleus accumbens ROIs (Table 2). This implies that using a trait measure to predict dopamine synthesis capacity resulted in a worse performance than simply predicting the average dopamine synthesis capacity – in other words, ignoring individual differences altogether. The cross-validated RMSE values were approximately 0.002 for all trait measures (Table 2), which is a substantial amount of error when considering that the interquartile range of dopamine synthesis capacity was approximately 0.003 (Supplementary Figure 1). This is illustrated in Figure 3, which shows for each participant the errors of the predictions of dopamine synthesis capacity in the ROIs from each of the trait measures. Good predictive value would have resulted in small variance of the predictions from each repeat around the zero-line for all or nearly all participants. However, the current predictions have large errors and the direction and size of the prediction error varies greatly over participants and trait measures.

Permutation testing indicated that for all trait measures, the cross-validated predictive performance was not statistically significant (Table 2; all permutation p-values > 0.10). That is, the observed cross-validated R^2 and RMSE values were not different from those under the null hypothesis of no predictive power for each of the trait measures.

Table 2. Summary statistics of the cross-validated predictive accuracy of working memory capacity, trait impulsivity, spontaneous eye-blink rate, or subjective reward sensitivity for striatal dopamine synthesis capacity.

Trait measure	Striatal ROI	metric: R^2			metric: RMSE		
		mean	std_err	perm_p	mean	std_err	perm_p
Digit Span	caudate nucleus	-0.19812	0.010189	0.617	0.002054	1.21E-05	0.6242
	putamen	-0.19854	0.010929	0.6048	0.002222	1.43E-05	0.4672
	nucleus accumbens	-0.20066	0.011087	0.6154	0.001895	1.29E-05	0.5174
Listening Span	caudate nucleus	-0.2009	0.01004	0.6272	0.002056	1.21E-05	0.6686
	putamen	-0.20468	0.01074	0.6246	0.002227	1.39E-05	0.5344
	nucleus accumbens	-0.20312	0.010809	0.6262	0.001898	1.28E-05	0.5624
BIS-11	caudate nucleus	-0.3554	0.019555	0.6562	0.00212	1.46E-05	0.71
	putamen	-0.42078	0.032679	0.7408	0.002298	1.60E-05	0.7188
	nucleus accumbens	-0.3709	0.02575	0.6382	0.001977	1.50E-05	0.6384
sEBR	caudate nucleus	-0.20731	0.010552	0.6382	0.002077	1.22E-05	0.748
	putamen	-0.18209	0.010114	0.5242	0.0022	1.31E-05	0.5688
	nucleus accumbens	-0.16276	0.008713	0.4236	0.001874	1.31E-05	0.335
BAS	caudate nucleus	-0.16081	0.01069	0.461	0.002022	1.27E-05	0.187
	putamen	-0.16465	0.011264	0.4672	0.002189	1.44E-05	0.1226
	nucleus accumbens	-0.16523	0.011255	0.4682	0.001865	1.29E-05	0.1468

R^2: coefficient of determination; RMSE: root mean square error; std_err: standard error; perm_p: p-value based on 5000 permutations; BIS-11: trait impulsivity questionnaire; sEBR: spontaneous eye-blink rate; BAS: Behavioural Activation Scale to measure subjective reward sensitivity.
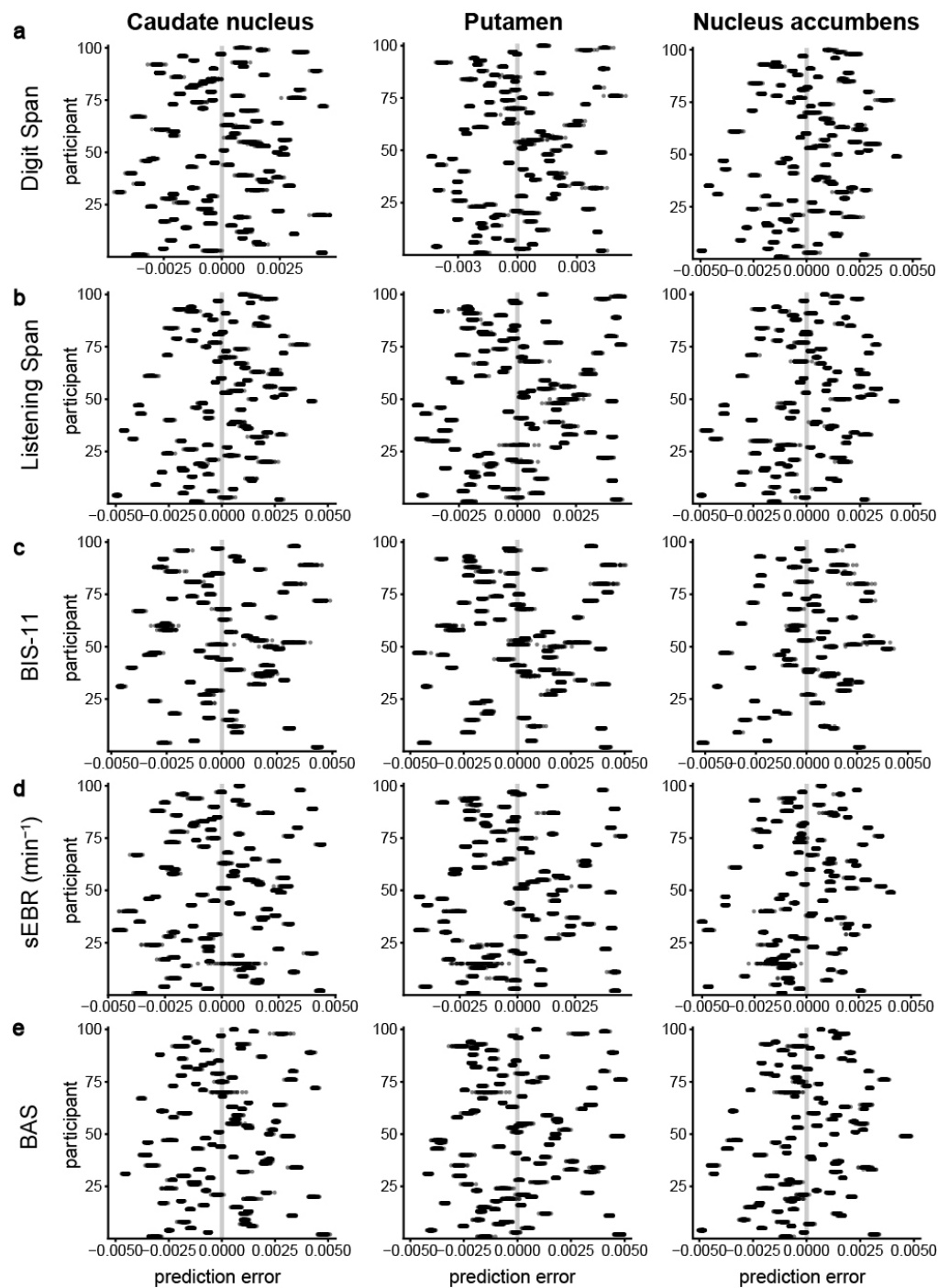
Figure 3. Cross-validation results of the predictive performance of working memory capacity, trait impulsivity, spontaneous eye-blink rate, or subjective reward sensitivity for striatal dopamine synthesis capacity. *Every plot shows for each participant the error of the prediction of dopamine synthesis capacity in the caudate nucleus (left column), putamen (middle column) or nucleus accumbens ROIs (right column) from **(a)** working memory capacity measured with the Digit Span task (N = 94), **(b)** working memory capacity measured with the Listening Span task (N = 94), **(c)** trait impulsivity measured with the BIS-11 questionnaire (N = 66), **(d)** spontaneous eye-blink rate (N = 92), or **(e)** subjective reward sensitivity measured with the Behavioural Activation Scale (N = 94). Each black dot represents the prediction error of one of 100 repeats of the k-fold cross-validation (k=10). For each panel, the gray vertical line at zero represents perfect predictive accuracy.*

Discussion

In this study, we provide evidence for a lack of correlations between striatal dopamine synthesis capacity, measured with [18F]-FDOPA PET imaging, and simple, off-the-shelf tests of working memory capacity, trait impulsivity, sEBR, and subjective reward sensitivity. Bayes Factor analyses provided evidence in favour of the absence of correlations, except for the BAS questionnaire, for which the evidence was inconclusive. Furthermore, cross-validation analyses revealed little out-of-sample predictive power of each trait measure for dopamine synthesis capacity.

The current work provides a direct assessment using human brain PET imaging of the relationships between these trait measures and striatal dopamine synthesis capacity on a much larger scale than previous work. Whereas some previous smaller-sample studies have found significant correlations of striatal dopamine synthesis capacity with working memory capacity (Cools et al., 2008; Landau et al., 2009) and with trait impulsivity (Petzold et al., 2019; Smith et al., 2015), our results corroborate other previous findings of a lack of correlations between striatal dopamine synthesis capacity and working memory capacity (Braskie et al., 2011, 2008; Klostermann et al., 2012), trait impulsivity (van Holst et al., 2018), and sEBR (Sescousse et al., 2018).

One potential source of variability between the different PET studies of dopamine synthesis capacity is the use of different radiotracers. For example, whereas the original studies reporting a positive correlation with striatal dopamine synthesis capacity used [18F]-FMT to index dopamine synthesis capacity (Cools et al., 2008; Landau et al., 2009), the current study used [18F]-FDOPA. This is particularly pertinent, because while both [18F]-FDOPA and [18F]-FMT ligands are substrates for aromatic amino acid decarboxylase, [18F]-FDOPA is subject to additional in vivo COMT metabolism, implying lower signal to noise ratio than [18F]-FMT (DeJesus et al., 1997), and perhaps also to some degree dopamine turnover rather than synthesis capacity (Dejesus et al., 2001). Future work is required to reconcile the growing body of literature demonstrating differential, sometimes even contrasting effects of dopamine synthesis capacity measured with [18F]-FMT and [18F]-FDOPA (Berry et al., 2016, 2018; Cools et al., 2009; Ito et al., 2011; Kumakura et al., 2010; van den Bosch et al., 2022). While we cannot exclude the possibility that the present lack of correlations reflects the use of a tracer with insufficient signal to noise, we consider it unlikely that the use of different radiotracers can fully explain the extant discrepancy for the following reasons. First, there is similar discrepancy between [18F]-FMT studies on working memory capacity, with some reporting positive effects (Cools et al., 2008; Landau et al., 2009) and other reporting no effects or negative effects (Braskie et al., 2011, 2008; Klostermann et al., 2012). Second, our analyses demonstrated not just a lack of evidence for the presence of correlations, but also the presence of evidence for the absence of correlations. Critically, the absence of correlations was not due to measurement error in the

estimates of striatal dopamine synthesis capacity or a lack of behavioural relevance of these estimates. The striatal [18F]-FDOPA uptake values are in the typical range (Supplementary Figure 1), and dopamine synthesis capacity in this dataset has been shown to account for (dopamine drug effects on) effort-based decision making, response vigour, reversal learning, and smartphone social activity in the expected direction (Hofmans et al., 2020, 2022; van den Bosch et al., 2022; Westbrook et al., 2020, 2021). More specifically, [18F]-FDOPA uptake in the striatum was associated positively with the value of cognitive effort (Westbrook et al., 2020), with the impact of average reward value on response vigour (Hofmans et al., 2022) and with dopaminergic drug-related changes in prediction error-related BOLD signal in the striatum (van den Bosch et al., 2022). The implication of this body of work is that more sophisticated and quantitative indices of value-based learning, motivation, and even daily logs of participants' social activity on their smartphone might be better proxy measures of striatal dopamine synthesis capacity than the simple trait measures reported here. This is perhaps not surprising because these more sophisticated measurements provide much more detailed characterizations of (latent) biases measured over many trials, and in the case of the smartphone logs, over many days, rather than single (self-report) measurements of more stable trait measures. Possibly, a more sophisticated trial-wise approach of measuring sEBR during task performance might relate more strongly to (fluctuations in) striatal dopamine activity, given that it correlates with cognitive performance (Ortega et al., 2022). Nevertheless, the predictive value of even these more sophisticated measurements should be established using replication and/or cross-validation of the models in previously unseen data.

It should be noted that the present results speak specifically to the relationship of the trait measures with striatal dopamine synthesis capacity. They do not speak to the presence or absence of correlations with other aspects of the dopamine system, such as dopamine $D_{2/3}$-receptor availability or dopamine release. Indeed, working memory, trait impulsivity, and sEBR have all been associated with $D_{2/3}$-receptor availability and/or dopamine release (Bäckman et al., 2011; Buckholtz et al., 2010; Clatworthy et al., 2009; Groman et al., 2014; Jongkees and Colzato, 2016; Kim et al., 2014), although the results for impulsivity and sEBR are mixed (Dang et al., 2017; Lee et al., 2009). Recent large-scale studies have demonstrated crucial involvement of both striatal and extrastriatal dopamine $D_{2/3}$-receptor availability in working memory performance using PET-fMRI measures (Garrett et al., 2022; Salami et al., 2019), but only prefrontal and not striatal receptor availability was significantly different between low and normal working memory groups (Salami et al., 2018). In addition to PET measures of striatal dopamine synthesis capacity, receptor availability, or dopamine release, future work might focus on other molecular imaging techniques and targets, such as single-photon emission computed tomography (SPECT) with ligands that bind to the dopamine transporter or prefrontal dopamine receptors. One such large-scale SPECT study in healthy volunteers (N=188) did not find

evidence for significant relationships between striatal dopamine transporter availability and working memory performance or trait impulsivity, in line with the current results for striatal dopamine synthesis capacity (Burke et al., 2011).

The trait measures of working memory capacity, trait impulsivity, and sEBR have been frequently found to account for individual differences in the cognitive effects of dopaminergic drugs, for example in the domain of reinforcement learning and Pavlovian biasing of instrumental action (Cavanagh et al., 2014; Cools et al., 2003, 2007; Frank and O'Reilly, 2006; Froböse et al., 2018; Kandroodi et al., 2021; Kimberg et al., 1997; Mehta et al., 2000; van der Schaaf et al., 2014). Such trait-dependent effects of dopamine drugs are reminiscent of the classic rate dependency hypothesis of psychostimulant effects (Dews, 1977), which states that manipulation effects depend on the baseline activity state of the system. We emphasize that the present results do not invalidate these previous findings but raise the hypothesis that the interactive effects between dopamine drug effects and trait characteristics reflect other factors than individual variation in baseline dopamine synthesis capacity. For example, dopaminergic drugs might have different effects on reinforcement learning in people with low and high working memory capacity, because of differences in the degree to which the drugs boost reinforcement learning or working memory strategies for task performance (Collins, 2018; Collins et al., 2014).

To conclude, the generally assumed link between baseline dopamine levels and the currently investigated trait measures has motivated popular use of these measures as a proxy for striatal dopamine activity instead of costly direct assessments of dopamine (synthesis) function with PET measurements. While such links are supported by evidence from patient or genetic studies and experimental animals, the interpretation of these behavioural indices as proxies for striatal dopamine levels requires robust direct evidence in humans for the existence of at least a strong correlation. The absence of such correlations observed here provides a strong cautionary message for future studies that may be tempted to use these relatively simple behavioural indices of working memory capacity, trait impulsivity, sEBR, or subjective reward sensitivity as a proxy for striatal dopamine synthesis capacity.

Methods

Participants

This study is part of a larger project (Määttä et al., 2021), for which 100 healthy volunteers were recruited, 50 women and 50 men (age at inclusion: ranged 18 to 43, mean (SD) = 23.0 (5.0) years). All participants provided written informed consent and were paid 309 euro on completion of the overarching study. The study was approved by the local ethics committee ("Commissie Mensgebonden Onderzoek", CMO region Arnhem-Nijmegen, The Netherlands:

protocol NL57538.091.16). People were recruited via an advertisement on the Radboud University electronic database for research participants, via a similar national database (www.proefbunny.nl), and via advertisement flyers around Nijmegen. Prerequisites for participation were an age between 18 and 45 years, Dutch as native language and right-handedness. Before admission to the study, participants were extensively screened for adverse medical and psychiatric conditions. Exclusion criteria included any current or previous psychiatric or neurological disorders, having a first-degree family member with a current or previous psychiatric disorder, clinically significant hepatic, cardiac, renal, metabolic or pulmonary disease, epilepsy, hyper or hypotension, habitual smoking or drug use, pregnancy, and MRI contraindications, such as unremovable metal parts in the body or claustrophobia.

Six participants dropped out before completion of the study because of discomfort in the MRI or PET scanner (N=4), personal reasons (N=1) or technical failure of the PET scanner (N=1). For the sEBR analyses, one participant was excluded due to poor data quality and one was excluded as an outlier (more than 5 SD's from the group mean), resulting in a final sample of N=92. For the impulsivity analyses, 67 participants completed the BIS-11 questionnaire (see subsection "Trait impulsivity" below for details), one of whom was excluded due to missing PET data, resulting in a final sample of N=66. For the Digit Span, Listening Span and BAS questionnaire, the full sample of N=94 was included.

General procedure

Data were collected as part of a large PET, pharmaco-fMRI study on the effects of methylphenidate and sulpiride on brain and cognition, employing a within-subject, placebo-controlled, double-blind cross-over design. For a detailed description of the testing sessions and tasks and measures collected, see Määttä et al. (2021).

The study consisted of five testing days separated by at least one week. The first was an intake session in which participants were screened for inclusion criteria, an anatomical MRI scan was obtained, and the measures of sEBR, and Listening Span and Digit Span of working memory capacity were collected. The second, third and fourth testing days were six-hour-long pharmaco-fMRI sessions in which participants performed a battery of dopamine-related tasks not reported here. On the fifth day, participants performed the Digit Span test once more, completed two behavioural tasks, and finally underwent an [18F]-FDOPA PET scan of the brain to measure their dopamine synthesis capacity.

Participants filled in the questionnaires of personality and trait characteristics online, after the third pharmaco-fMRI session and before the final testing day with PET scan (mean time difference = 32.45 days; standard error of mean = 3.14 days). The mean time difference between the intake session and PET session was 90.16 days, standard error of mean = 3.13 days.

Data acquisition and preprocessing

MRI

On the intake session, a whole-brain structural image was acquired to use for within-subject registration with the PET images, using a T1-weighted magnetization prepared, rapid-acquisition gradient echo sequence (192 sagittal slices; repetition time, 2300 ms; echo time, 3.03 ms; field of view: 256x256mm; flip angle, 8°; 256x256 matrix; 1.0mm in-plane resolution; 1.0mm slice thickness). The MRI experiment was performed on a 3T Siemens Magnetom Skyra MRI scanner at the Donders Institute, using a 32-channel head coil.

PET

The brain PET data were acquired on a state-of-the-art PET/CT scanner (Siemens Biograph mCT; Siemens Medical Systems, Erlangen, Germany) at the Department of Medical Imaging of the Radboud University Medical Center. We used the well-validated radiotracer [^{18}F]-FDOPA, which was synthesized at Radboud Translational Medicine BV (RTM BV) in Nijmegen. The tracer is a substrate for aromatic amino acid decarboxylase, the enzyme that converts DOPA into dopamine. The rate of conversion of [^{18}F]-FDOPA into dopamine provides an estimate of dopamine synthesis capacity. Fifty minutes before the PET scan started, participants received 150mg of carbidopa and 400mg of entacapone to minimize peripheral metabolism of [^{18}F]-FDOPA by peripheral decarboxylase and catechol-O-methyltransferase (COMT), respectively, thereby increasing signal to noise ratio in the brain (Boyes et al., 1986; Hoffman et al., 1992; Ishikawa et al., 1996; Léger et al., 1998).

The procedure started with a low-dose CT scan to use for attenuation correction of the PET images. Then, the [^{18}F]-FDOPA tracer was administered (approximately 185 MBq) via a bolus injection in the antecubital vein and the PET scan was started. Dynamic PET data (4x4x3 mm voxel size; 5 mm slice thickness; 200x200x75 matrix) were acquired over 89 minutes and divided into 24 frames (4x1, 3x2, 3x3, 14x5 min). Data were reconstructed with weighted attenuation correction and time-of-flight recovery, scatter corrected, and smoothed with a 3 mm full-width-at-half-maximum (FWHM) kernel.

The PET data were preprocessed and analyzed using SPM12. All frames were realigned to the mean image to correct for head motion between scans. The realigned frames were then co-registered to the structural MRI scan, using the mean PET image of the first 11 frames (corresponding to the first 24 minutes), which has a better range in image contrast than a mean image over the whole scan time in regions other than the striatum. Presynaptic dopamine synthesis capacity was quantified as the tracer influx rate k_i^{cer} (min^{-1}) per voxel with graphical analysis for irreversible tracer binding using Gjedde-Patlak modeling (Patlak and Blasberg, 1985; Patlak et al., 1983). The analysis was performed on the images corresponding to 24-89 minutes, which is the period after the irreversible

compartments had reached equilibrium and the input function to the striatum had become linear. The k_i^{cer} values represent the rate of tracer accumulation relative to the reference region of cerebellar grey matter, where the density of dopamine receptors and metabolites is extremely low compared to the striatum (Farde et al., 1986; Hall et al., 1999). The cerebellar grey matter mask was obtained using FreeSurfer segmentation of each individual's anatomical MRI scan, as implemented in *fMRIPREP*. Resulting k_i^{cer} maps were spatially normalized to MNI space, smoothed with an 8mm FWHM kernel and brain extracted.

After preprocessing we extracted the mean k_i^{cer} values from the caudate nucleus, putamen and nucleus accumbens in native subject space. The masks for these regions of interest (ROIs) were based on an independent, functional connectivity-based parcellation of the striatum (Supplementary Figure 7; Piray et al., 2017). The extracted k_i^{cer} values represent the dopamine synthesis capacity in the ROIs, and were used to correlate the putative proxy measures with.

Working memory

Working memory capacity was indexed with the Digit Span test (Groth-Marnat, 1997) and Listening Span test (Daneman and Carpenter, 1980). Both tasks were computerized.

In the Digit Span test, participants started with the forward section, in which they listened to a series of numbers and were required to repeat the correct numbers in order. The series increased in length (starting at 3 digits) until the participant failed two attempts on a series length, or until the maximum length of 9 digits was completed. Next, in the backwards section, participants again listened to series of numbers but were required to repeat the correct numbers in reverse order. This series started with a length of 2 digits and increased until the participant failed two attempts on a series length, or until a maximum length of 8 digits. The Digit Span score on each section was the number of correctly recited series, and the total score was the sum of the scores on the forward and backward sections. The Digit Span was performed twice, once on the intake session and once on the final testing day, before the PET scan (test-retest correlation: $\rho = 0.8$). The scores on each day were averaged to obtain the final Digit Span scores for the forward and backward sections, as well as the total scores.

The Listening Span test consists of sets of pre-recorded sentences, increasing in size from 2 to 7 sentences. Participants were presented with the sentences and were simultaneously required to answer written verification questions regarding the content of each sentence. At the end of each set, subjects recalled the final word of each sentence in the order of presentation. The Listening Span was defined as the set size for which the participant correctly recalled the final words on at least two out of three trials. Listening span increased with half a point when only one trial of the next level was correct. In

addition to the Listening Span, the total number of final words that were correctly recalled was used as an additional measure.

Trait impulsivity

Trait impulsivity was assessed with the Barratt Impulsiveness Scale (BIS-11; Patton et al., 1995). The BIS-11 is a self-report questionnaire, consisting of 30 statements about common (non)impulsive behaviours and preferences, and participants indicate their level of endorsement on a 4-point Likert scale. The BIS-11 total impulsivity scores reflect the tendency towards impulsivity. Participants completed the questionnaire at home between test days.

Due to an experimenter error, a prototype of the questionnaire, known as BIS-11A, was originally administered. That version has never been validated and it contains both differently phrased as well as completely different questions compared with the validated BIS-11 questionnaire (https://www.impulsivity.org/measurement/bis11/). When the error was discovered after the completion of the study, the intended version of the questionnaire (i.e., BIS-11) was sent to the participants, of whom 67 completed it.

sEBR

The sEBR data were collected using electro-oculography (EOG), recorded on a BrainVision Recorder system (Brain products GmbH, Munich, Germany) with 200Hz sampling rate. We followed automatic and manual procedures for data acquisition, preprocessing and data analysis of the EOG data (Sescousse et al., 2018). The EOG data were acquired during the day (before 5 pm) over a period of (up to) 10 minutes, using two vertical and two horizontal Ag-AgCl electrodes placed around the eyes. During the study, the length of recording was increased from 6 to 10 min following recommendation by external colleagues; 28 participants were recorded for 6 min, and the 72 remaining participants were recorded for 10 min. The vertical EOG (vEOG) signal, used for assessing eye blinks, was obtained from a bipolar montage using the electrodes placed above and below the right eye. The horizontal EOG (hEOG) signal, used to exclude artefacts produced by saccades and muscle activity, was obtained from bipolar montage using the electrodes placed lateral to the eternal canthi, and the ground electrode was placed on the right mastoid.

Participants were comfortably seated facing a white wall from about 1.5 m distance and were asked to look ahead while they believed the experimenter was checking signal quality in preparation of a system calibration. The measurement took place during what the participants believed was a signal quality check. This cover story was meant to prevent the participants from being aware that they were being recorded. The experimenter was outside the room during the measurement. No instructions about blinking were given, and care was taken to not direct participants' attention to their eyes. However, due to a communication error, 9 participants received inconsistent instructions and were

incorrectly instructed to stare at the wall. Excluding these participants slightly increased the coefficients of the correlations with dopamine synthesis capacity, but not enough to become statistically significant (see Results).

The EOG data were rectified and band-pass filtered between 0.5 and 20Hz using the Fieldtrip toolbox in Matlab (Oostenveld et al. (2010); http://fieldtriptoolbox.org/; Mathworks Inc.; https://nl.mathworks.com/products/matlab.html). Eye blinks were detected using an automated procedure based on a voltage change passing a threshold that was set individually per participant (range 100 µV) in a time interval of 400 ms (Slagter et al., 2010). The vEOG signal was visually inspected by two researchers independently to assess detection accuracy. Blinks were manually added or removed according to the threshold definition of a blink when appropriate, and potential artefacts from saccades or muscle activity were removed when they were detected in the hEOG signal. Because the inter-rater reliability of the independent scoring of the sEBR values was high ($\alpha = 0.98$), the analyses were performed on the average blink rate determined by the two researchers.

Subjective reward sensitivity

We measured trait characteristics of reward sensitivity with the Behavioural Activation Scale (BAS; Carver and White (1994); Franken et al. (2005)). This scale consists of 17 items that are scored on a 4-point Likert scale, and can be split into three subscales: Reward-Responsiveness, Drive and Fun-Seeking. These were designed to assess personality constructs of reinforcement sensitivity theory (Carver and White, 1994).

Statistical analysis

The primary correlation analyses were performed with dopamine synthesis capacity for each of the three striatal ROIs and the total Digit Span score and Listening Span score, total BIS-11 score, sEBR values, and total BAS score. We subsequently explored the correlations between dopamine synthesis capacity and sub-sections of the proxy measures: forward and backward Digit Span, total words recalled in the Listening Span task, impulsivity scores on the attentional, motor and nonplanning subscales of the BIS-11, and scores on the Reward Responsiveness, Fun-Seeking and Drive subscales of the BAS questionnaire. Statistics for the correlations with the subscales are provided in the Supplementary Information (Supplementary Figures 3–5) but not used for inference on statistical significance, given the exploratory nature of these analyses.

All statistical analyses were performed in R (version 4.0.1) (Team, 2020). We used one-sided Pearson correlation analyses to test the statistical significance of positive relationships between the proxy measures and dopamine synthesis capacity in the three striatal ROIs. For each proxy, we corrected the p-values of the correlation coefficients for the comparisons in three ROIs using Holm-Bonferroni correction. Since many of the

corrected p-values were rounded to the upper limit of 1, we also report the uncorrected values to give a sense of precision.

For more precise localization of any correlation effects, we also performed voxel-wise one-sample t-tests of the PET k_i^{cer} data with each proxy measure as a covariate in separate models. We report striatal activation results for clusters surviving peak-level family-wise error (FWE) correction at $p < 0.05$ after small-volume correction for the combination of the three striatal ROI masks. These analyses were run using Statistical Parametric Mapping 12 (SPM12; https://www.fil.ion.ucl.ac.uk/spm/software/spm12/) running in MATLAB.

In addition to the confirmatory Pearson correlation tests, we used Bayes Factor correlation analyses to quantify the evidence in favour of the null hypothesis (H0) that there is not a positive correlation versus the alternative hypothesis (H1) that there is a positive correlation. The Bayes Factor (BF_{01}) reports the ratio of the evidence for H0 over H1, given the data. Thus, a BF_{01} greater than 1 indicates stronger evidence for H0 than H1, and vice versa for a BF_{01} smaller than 1. We ran the Bayesian correlation analyses with uninformative (flat) prior beta distributions over the (0,1) interval. We also checked the robustness of the resulting Bayes Factors by recalculating the Bayes Factors for each correlation using a range of strong to weak beta priors (ranging from a width of 0 to 2). For completeness, we also quantified the evidence for the non-directional hypotheses of no correlation (H0) versus a non-zero correlation (H1), using Bayesian correlation analyses over the (-1,1) interval with uninformative priors. The Bayes Factor analyses were performed using the function `correlationBF` of the `BayesFactor` package in R [Ly et al. (2016); version 0.9.12-4.2].

Predictive modeling

We used *k*-fold cross-validation and permutation testing to estimate to what extent the trait variables could be used to predict dopamine synthesis capacity for previously unseen participants. These resampling methods were applied to simple linear regression models, in which dopamine synthesis capacity in one of the three striatal ROIs served as the outcome variable and one of the trait measures served as the predictor variable.

In *k*-fold cross-validation, the original data is randomly split into k subsamples (i.e., folds) of roughly equal size. The model is initially fit to a 'training' dataset comprising *k*-1 folds. The trained model is then applied to the single remaining fold that was held back as the 'validation' data, to evaluate the predictive accuracy. This process is repeated *k* times, so that each fold is used exactly once as the validation data. The entire *k*-fold cross-validation procedure can be repeated several times, to avoid spurious results due to the random initial split into *k* folds. Here, we performed 10-fold cross-validation with 100 repeats.

Permutation sampling is used to construct a null distribution of the model's predictive accuracy, which can be compared to the estimated predictive accuracy for the original data to establish whether the model offers predictive performance above chance. For a single permutation, the outcome variable is randomly shuffled whereas the predictor variable is unaltered, thereby eliminating the participant-wise link between variables. This permuted dataset is then subjected to 10-fold cross-validation, to estimate the model's predictive accuracy. By repeating this process many times (here, 5000 times), we obtain a distribution of the model's predictive accuracy under the null hypothesis. The permutation p-value is defined as the proportion of permutations for which the model's predictive accuracy is as good or greater than the predictive accuracy for the original data.

We defined predictive accuracy as the model's coefficient of determination, R^2. If $\hat{y}_i$ is the predicted value of the i-th sample and y_i is the corresponding true value for a total of n samples, the estimated R^2 is defined as:

$$R^2(y, \hat{y}) = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

where $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$. An R^2 of 1 indicates perfect predictive accuracy. A constant (intercept-only) model that merely predicts the expected value of y, ignoring individual differences as a function of the predictor variable, would correspond to an R^2 of 0. The model can be arbitrarily worse than an intercept-only model, and therefore R^2 can be negative.

We additionally examined the root mean square error, RMSE, which represents the quadratic mean of the difference between the true values and predicted values:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

In contrast to R^2, this metric is represented on the same scale as the outcome variable. An RMSE of 0 indicates perfect predictive accuracy, and higher scores correspond to worse accuracy.

Acknowledgements

Competing interests

The authors declare no competing interests.

References

Allen EA, Erhardt EB, Calhoun VD. 2012. Data Visualization in the Neurosciences: Overcoming the Curse of Dimensionality. *Neuron* **74**:603–608. doi:10.1016/j.neuron.2012.05.001

Barch DM, Ceaser A. 2012. Cognition in schizophrenia: Core psychological and neural mechanisms. *Trends in Cognitive Sciences*, Special Issue: Cognition in Neuropsychiatric Disorders **16**:27–34. doi:10.1016/j.tics.2011.11.015

Bäckman L, Nyberg L, Soveri A, Johansson J, Andersson M, Dahlin E, Neely AS, Virta J, Laine M, Rinne JO. 2011. Effects of Working-Memory Training on Striatal Dopamine Release. *Science* **333**:718–718. doi:10.1126/science.1204978

Berry AS, Shah VD, Baker SL, Vogel JW, O'Neil JP, Janabi M, Schwimmer HD, Marks SM, Jagust WJ. 2016. Aging Affects Dopaminergic Neural Mechanisms of Cognitive Flexibility. *Journal of Neuroscience* **36**:12559–12569. doi:10.1523/JNEUROSCI.0626-16.2016

Berry AS, Shah VD, Furman DJ, White III RL, Baker SL, O'Neil JP, Janabi M, D'Esposito M, Jagust WJ. 2018. Dopamine Synthesis Capacity is Associated with D2/3 Receptor Binding but Not Dopamine Release. *Neuropsychopharmacology* **43**:1201–1211. doi:10.1038/npp.2017.180

Boyes BE, Cumming P, Martin WRW, McGeer EG. 1986. Determination of plasma [18F]-6-fluorodopa during positron emission tomography: Elimination and metabolism in carbidopa treated subjects. *Life Sciences* **39**:2243–2252. doi:10.1016/0024-3205(86)90403-0

Braskie MN, Landau SM, Wilcox CE, Taylor SD, O'Neil JP, Baker SL, Madison CM, Jagust WJ. 2011. Correlations of striatal dopamine synthesis with default network deactivations during working memory in younger adults. *Human Brain Mapping* **32**:947–961. doi:10.1002/hbm.21081

Braskie MN, Wilcox CE, Landau SM, O'Neil JP, Baker SL, Madison CM, Kluth JT, Jagust WJ. 2008. Relationship of Striatal Dopamine Synthesis Capacity to Age and Cognition. *Journal of Neuroscience* **28**:14320–14328. doi:10.1523/JNEUROSCI.3729-08.2008

Buckholtz JW, Treadway MT, Cowan RL, Woodward ND, Li R, Ansari MS, Baldwin RM, Schwartzman AN, Shelby ES, Smith CE, Kessler RM, Zald DH. 2010. Dopaminergic Network Differences in Human Impulsivity. *Science* **329**:532–532. doi:10.1126/science.1185778

Burke SM, Giessen E van de, Win M de, Schilt T, Herk M van, Brink W van den, Booij J. 2011. Serotonin and dopamine transporters in relation to neuropsychological functioning,

personality traits and mood in young adult healthy subjects. *Psychological Medicine* **41**:419–429. doi:10.1017/S0033291710000486

Carver CS, White TL. 1994. Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: The BIS/BAS Scales. *Journal of Personality and Social Psychology* **67**:319–333. doi:10.1037/0022-3514.67.2.319

Cavanagh JF, Masters SE, Bath K, Frank MJ. 2014. Conflict acts as an implicit cost in reinforcement learning. *Nature Communications* **5**:5394. doi:10.1038/ncomms6394

Clatworthy PL, Lewis SJG, Brichard L, Hong YT, Izquierdo D, Clark L, Cools R, Aigbirhio FI, Baron J-C, Fryer TD, Robbins TW. 2009. Dopamine Release in Dissociable Striatal Subregions Predicts the Different Effects of Oral Methylphenidate on Reversal Learning and Spatial Working Memory. *Journal of Neuroscience* **29**:4690–4696. doi:10.1523/JNEUROSCI.3266-08.2009

Collins AGE. 2018. The Tortoise and the Hare: Interactions between Reinforcement Learning and Working Memory. *Journal of Cognitive Neuroscience* **30**:1422–1432. doi:10.1162/jocn_a_01238

Collins AGE, Brown JK, Gold JM, Waltz JA, Frank MJ. 2014. Working Memory Contributions to Reinforcement Learning Impairments in Schizophrenia. *The Journal of Neuroscience* **34**:13747–13756. doi:10.1523/JNEUROSCI.0989-14.2014

Collins P, Wilkinson LS, Everitt BJ, Robbins TW, Roberts AC. 2000. The effect of dopamine depletion from the caudate nucleus of the common marmoset (Callithrix jacchus) on tests of prefrontal cognitive function. *Behavioral Neuroscience* **114**:3–17. doi:10.1037/0735-7044.114.1.3

Colzato LS, van den Wildenberg WPM, van Wouwe NC, Pannebakker MM, Hommel B. 2009. Dopamine and inhibitory action control: Evidence from spontaneous eye blink rates. *Experimental Brain Research* **196**:467–474. doi:10.1007/s00221-009-1862-x

Colzato LS, Wildenberg WPM van den, Hommel B. 2008. Reduced Spontaneous Eye Blink Rates in Recreational Cocaine Users: Evidence for Dopaminergic Hypoactivity. *PLOS ONE* **3**:e3461. doi:10.1371/journal.pone.0003461

Cools R, Barker RA, Sahakian BJ, Robbins TW. 2003. L-Dopa medication remediates cognitive inflexibility, but increases impulsivity in patients with Parkinson's disease. *Neuropsychologia* **41**:1431–1441. doi:10.1016/S0028-3932(03)00117-9

Cools R, Frank MJ, Gibbs SE, Miyakawa A, Jagust W, D'Esposito M. 2009. Striatal Dopamine Predicts Outcome-Specific Reversal Learning and Its Sensitivity to Dopaminergic Drug Administration. *The Journal of Neuroscience* **29**:1538–1543. doi:10.1523/JNEUROSCI.4467-08.2009

Cools R, Gibbs SE, Miyakawa A, Jagust W, D'Esposito M. 2008. Working Memory Capacity Predicts Dopamine Synthesis Capacity in the Human Striatum. *Journal of Neuroscience* **28**:1208–1212. doi:10.1523/JNEUROSCI.4475-07.2008

Cools R, Sheridan M, Jacobs E, D'Esposito M. 2007. Impulsive Personality Predicts Dopamine-Dependent Changes in Frontostriatal Activity during Component Processes of Working Memory. *Journal of Neuroscience* **27**:5506–5514. doi:10.1523/JNEUROSCI.0601-07.2007

Cools R, Tichelaar JG, Helmich RCG, Bloem BR, Esselink RAJ, Smulders K, Timmer MHM. 2022. Chapter 13 - Role of dopamine and clinical heterogeneity in cognitive dysfunction in Parkinson's disease In: Narayanan NS, Albin RL, editors. Progress in Brain Research, Cognition in Parkinson's Disease. Elsevier. pp. 309–343. doi:10.1016/bs.pbr.2022.01.012

Costumero V, Barrós-Loscertales A, Bustamante JC, Ventura-Campos N, Fuentes P, Rosell-Negre P, Ávila C. 2013. Reward Sensitivity Is Associated with Brain Activity during Erotic Stimulus Processing. *PLOS ONE* **8**:e66940. doi:10.1371/journal.pone.0066940

Dalley JW, Fryer TD, Brichard L, Robinson ESJ, Theobald DEH, Lääne K, Peña Y, Murphy ER, Shah Y, Probst K, Abakumova I, Aigbirhio FI, Richards HK, Hong Y, Baron J-C, Everitt BJ, Robbins TW. 2007. Nucleus Accumbens D2/3 Receptors Predict Trait Impulsivity and Cocaine Reinforcement. *Science* **315**:1267–1270. doi:10.1126/science.1137073

Daneman M, Carpenter PA. 1980. Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior* **19**:450–466. doi:10.1016/S0022-5371(80)90312-6

Dang LC, Samanez-Larkin GR, Castrellon JJ, Perkins SF, Cowan RL, Newhouse PA, Zald DH. 2017. Spontaneous Eye Blink Rate (EBR) Is Uncorrelated with Dopamine D2 Receptor Availability and Unmodulated by Dopamine Agonism in Healthy Adults. *eNeuro* **4**. doi:10.1523/ENEURO.0211-17.2017

DeJesus OT, Endres CJ, Shelton SE, Nickles RJ, Holden JE. 1997. Evaluation of Fluorinated m-Tyrosine Analogs as PET Imaging Agents of Dopamine Nerve Terminals: Comparison with 6-Fluorodopa. *Journal of Nuclear Medicine* 7.

Dejesus OT, Endres CJ, Shelton SE, Nickles RJ, Holden JE. 2001. Noninvasive assessment of aromatic L-amino acid decarboxylase activity in aging rhesus monkey brain in vivo. *Synapse* **39**:58–63. doi:10.1002/1098-2396(20010101)39:1<58::AID-SYN8>3.0.CO;2-B

Depue RA, Collins PF. 1999. Neurobiology of the structure of personality: Dopamine, facilitation of incentive motivation, and extraversion. *Behavioral and Brain Sciences* **22**:491–517. doi:10.1017/S0140525X99002046

Dews PB. 1977. Rate-dependency hypothesis. *Science* **198**:1182–1183. doi:10.1126/science.563103

Farde L, Hall H, Ehrin E, Sedvall G. 1986. Quantitative analysis of D2 dopamine receptor binding in the living human brain by PET. *Science* **231**:258–261. doi:10.1126/science.2867601

Frank MJ, Fossella JA. 2011. Neurogenetics and Pharmacology of Learning, Motivation, and Cognition. *Neuropsychopharmacology* **36**:133–152. doi:10.1038/npp.2010.96

Frank MJ, O'Reilly RC. 2006. A mechanistic account of striatal dopamine function in human cognition: Psychopharmacological studies with cabergoline and haloperidol. *Behavioral Neuroscience* **120**:497–517. doi:10.1037/0735-7044.120.3.497

Franken IHA, Muris P, Rassin E. 2005. Psychometric Properties of the Dutch BIS/BAS Scales. *Journal of Psychopathology and Behavioral Assessment* **27**:25–30. doi:10.1007/s10862-005-3262-2

Fröbose MI, Swart JC, Cook JL, Geurts DEM, den Ouden HEM, Cools R. 2018. Catecholaminergic modulation of the avoidance of cognitive control. *Journal of Experimental Psychology General* **147**:1763–1781. doi:10.1037/xge0000523

Garrett DD, Kloosterman NA, Epp S, Chopurian V, Kosciessa JQ, Waschke L, Skowron A, Shine JM, Perry A, Salami A, Rieckmann A, Papenberg G, Wåhlin A, Karalija N, Andersson M, Riklund K, Lövdén M, Bäckman L, Nyberg L, Lindenberger U. 2022. Dynamic regulation of neural variability during working memory reflects dopamine, functional integration, and decision-making. doi:10.1101/2022.05.05.490687

Groman SM, James AS, Seu E, Tran S, Clark TA, Harpster SN, Crawford M, Burtner JL, Feiler K, Roth RH, Elsworth JD, London ED, Jentsch JD. 2014. In the Blink of an Eye: Relating Positive-Feedback Sensitivity to Striatal Dopamine D2-Like Receptors through Blink Rate. *Journal of Neuroscience* **34**:14443–14454. doi:10.1523/JNEUROSCI.3037-14.2014

Groth-Marnat G. 1997. The Wechsler Intelligence ScalesHandbook of Psychological Assessment. Hoboken, NJ, NCA: John Wiley & Sons Inc. pp. 175–176.

Hall H, Halldin C, Guilloteau D, Chalon S, Emond P, Besnard JC, Farde L, Sedvall G. 1999. Visualization of the Dopamine Transporter in the Human Brain Postmortem with the New Selective Ligand [125I]PE2I. *NeuroImage* **9**:108–116. doi:10.1006/nimg.1998.0366

Hoffman JM, Melega WP, Hawk TC, Grafton SC, Luxen A, Mahoney DK, Barrio JR, Huang S-C, Mazziotta JC, Phelps ME. 1992. The Effects of Carbidopa Administration on 6-[18F]Fluoro-L-DOPA Kinetics in Positron Emission Tomography. *Journal of Nuclear Medicine* **33**:1472–1477.

Hofmans L, Papadopetraki D, van den Bosch R, Määttä JI, Fröbose MI, Zandbelt BB, Westbrook A, Verkes R-J, Cools R. 2020. Methylphenidate boosts choices of mental labor over leisure depending on striatal dopamine synthesis capacity. *Neuropsychopharmacology* **45**:2170–2179. doi:10.1038/s41386-020-00834-1

Hofmans L, Westbrook A, van den Bosch R, Booij J, Verkes R-J, Cools R. 2022. Effects of average reward rate on vigor as a function of individual variation in striatal dopamine. *Psychopharmacology* **239**:465–478. doi:10.1007/s00213-021-06017-0

Ishikawa T, Dhawan V, Chaly T, Robeson W, Belakhlef A, Mandel F, Dahl R, Margouleff C, Eidelberg D. 1996. Fluorodopa Positron Emission Tomography with an Inhibitor of Catechol-O-Methyltransferase: Effect of the Plasma 3-O-Methyldopa Fraction on Data Analysis. *Journal of Cerebral Blood Flow & Metabolism* **16**:854–863. doi:10.1097/00004647-199609000-00010

Ito H, Kodaka F, Takahashi H, Takano H, Arakawa R, Shimada H, Suhara T. 2011. Relation between Presynaptic and Postsynaptic Dopaminergic Functions Measured by Positron Emission Tomography: Implication of Dopaminergic Tone. *Journal of Neuroscience* **31**:7886–7890. doi:10.1523/JNEUROSCI.6024-10.2011

James AS, Groman SM, Seu E, Jorgensen M, Fairbanks LA, Jentsch JD. 2007. Dimensions of Impulsivity Are Associated with Poor Spatial Working Memory Performance in Monkeys. *Journal of Neuroscience* **27**:14358–14364. doi:10.1523/JNEUROSCI.4508-07.2007

Jentsch JD, Taylor JR. 1999. Impulsivity resulting from frontostriatal dysfunction in drug abuse: Implications for the control of behavior by reward-related stimuli. *Psychopharmacology* **146**:373–390. doi:10.1007/PL00005483

Jongkees BJ, Colzato LS. 2016. Spontaneous eye blink rate as predictor of dopamine-related cognitive functionA review. *Neuroscience & Biobehavioral Reviews* **71**:58–82. doi:10.1016/j.neubiorev.2016.08.020

Kandroodi MR, Cook JL, Swart JC, Froböse MI, Geurts DEM, Vahabie A-H, Nili Ahmadabadi M, Cools R, den Ouden HEM. 2021. Effects of methylphenidate on reinforcement learning depend on working memory capacity. *Psychopharmacology*. doi:10.1007/s00213-021-05974-w

Kellendonk C, Simpson EH, Polan HJ, Malleret G, Vronskaya S, Winiger V, Moore H, Kandel ER. 2006. Transient and Selective Overexpression of Dopamine D2 Receptors in the Striatum Causes Persistent Abnormalities in Prefrontal Cortex Functioning. *Neuron* **49**:603–615. doi:10.1016/j.neuron.2006.01.023

Kim J-H, Son Y-D, Kim H-K, Lee S-Y, Kim Y-B, Cho Z-H. 2014. Dopamine D2/3 receptor availability and human cognitive impulsivity: A high-resolution positron emission tomography imaging study with [11C]Raclopride. *Acta Neuropsychiatrica* **26**:35–42. doi:10.1017/neu.2013.29

Kimberg DY, D'Esposito M, Farah MJ. 1997. Effects of bromocriptine on human subjects depend on working memory capacity. *NeuroReport* **8**:3581–3585.

Klostermann EC, Braskie MN, Landau SM, O'Neil JP, Jagust WJ. 2012. Dopamine and frontostriatal networks in cognitive aging. *Neurobiology of Aging* **33**:623.e15–623.e24. doi:10.1016/j.neurobiolaging.2011.03.002

Kumakura Y, Vernaleken I, Buchholz H-G, Borghammer P, Danielsen E, Gründer G, Heinz A, Bartenstein P, Cumming P. 2010. Age-dependent decline of steady state dopamine storage capacity of human brain: An FDOPA PET study. *Neurobiology of Aging* **31**:447–463. doi:10.1016/j.neurobiolaging.2008.05.005

Landau SM, Lal R, O'Neil JP, Baker S, Jagust WJ. 2009. Striatal Dopamine and Working Memory. *Cerebral Cortex* **19**:445–454. doi:10.1093/cercor/bhn095

Lee B, London ED, Poldrack RA, Farahi J, Nacca A, Monterosso JR, Mumford JA, Bokarius AV, Dahlbom M, Mukherjee J, Bilder RM, Brody AL, Mandelkern MA. 2009. Striatal Dopamine D2/D3 Receptor Availability Is Reduced in Methamphetamine Dependence and Is Linked

to Impulsivity. *Journal of Neuroscience* **29**:14734–14740. doi:10.1523/JNEUROSCI.3765-09.2009

Léger G, Gjedde A, Kuwabara H, Guttman M, Cumming P. 1998. Effect of catechol-O-methyltransferase inhibition on brain uptake of [18F]Fluorodopa: Implications for compartmental modelling and clinical usefulness. *Synapse* **30**:351–361. doi:10.1002/(SICI)1098-2396(199812)30:4<351::AID-SYN2>3.0.CO;2-2

Locke HS, Braver TS. 2008. Motivational influences on cognitive control: Behavior, brain activation, and individual differences. *Cognitive, Affective, & Behavioral Neuroscience* **8**:99–112. doi:10.3758/CABN.8.1.99

Loken E, Gelman A. 2017. Measurement error and the replication crisis. *Science* **355**:584–585. doi:10.1126/science.aal3618

Ly A, Verhagen J, Wagenmakers E-J. 2016. Harold Jeffreys's default Bayes factor hypothesis tests: Explanation, extension, and application in psychology. *Journal of Mathematical Psychology*, Bayes Factors for Testing Hypotheses in Psychological Research: Practical Relevance and New Developments **72**:19–32. doi:10.1016/j.jmp.2015.06.004

Maffei A, Angrilli A. 2018. Spontaneous eye blink rate: An index of dopaminergic component of sustained attention and fatigue. *International Journal of Psychophysiology* **123**:58–63. doi:10.1016/j.ijpsycho.2017.11.009

Marek S, Tervo-Clemmens B, Calabro FJ, Montez DF, Kay BP, Hatoum AS, Donohue MR, Foran W, Miller RL, Hendrickson TJ, Malone SM, Kandala S, Feczko E, Miranda-Dominguez O, Graham AM, Earl EA, Perrone AJ, Cordova M, Doyle O, Moore LA, Conan GM, Uriarte J, Snider K, Lynch BJ, Wilgenbusch JC, Pengo T, Tam A, Chen J, Newbold DJ, Zheng A, Seider NA, Van AN, Metoki A, Chauvin RJ, Laumann TO, Greene DJ, Petersen SE, Garavan H, Thompson WK, Nichols TE, Yeo BTT, Barch DM, Luna B, Fair DA, Dosenbach NUF. 2022. Reproducible brain-wide association studies require thousands of individuals. *Nature* **603**:654–660. doi:10.1038/s41586-022-04492-9

Marklund P, Larsson A, Elgh E, Linder J, Riklund KÅ, Forsgren L, Nyberg L. 2009. Temporal dynamics of basal ganglia under-recruitment in Parkinson's disease: Transient caudate abnormalities during updating of working memory. *Brain* **132**:336–346. doi:10.1093/brain/awn309

Martinez E, Pasquereau B, Drui G, Saga Y, Météreau É, Tremblay L. 2020. Ventral striatum supports Methylphenidate therapeutic effects on impulsive choices expressed in temporal discounting task. *Scientific Reports* **10**:716. doi:10.1038/s41598-020-57595-6

Määttä JI, van den Bosch R, Papadopetraki D, Hofmans L, Lambregts B, Westbrook A, Verkes R-J, Cools R. 2021. Predicting effects of methylphenidate and sulpiride on brain and cognition: A pharmaco-fMRI, PET study. Design and descriptives. doi:10.31219/osf.io/d3h8e

Mehta MA, Owen AM, Sahakian BJ, Mavaddat N, Pickard JD, Robbins TW. 2000. Methylphenidate Enhances Working Memory by Modulating Discrete Frontal and

Parietal Lobe Regions in the Human Brain. *Journal of Neuroscience* **20**:RC65–RC65. doi:10.1523/JNEUROSCI.20-06-j0004.2000

Oostenveld R, Fries P, Maris E, Schoffelen J-M. 2010. FieldTrip: Open Source Software for Advanced Analysis of MEG, EEG, and Invasive Electrophysiological Data. *Computational Intelligence and Neuroscience* **2011**:e156869. doi:10.1155/2011/156869

Ortega J, Plaska CR, Gomes BA, Ellmore TM. 2022. Spontaneous Eye Blink Rate During the Working Memory Delay Period Predicts Task Accuracy. *Frontiers in Psychology* **13**.

Patlak CS, Blasberg RG. 1985. Graphical evaluation of blood-to-brain transfer constants from multiple-time uptake data. Generalizations. *Journal of Cerebral Blood Flow & Metabolism* **5**:584–590.

Patlak CS, Blasberg RG, Fenstermacher JD. 1983. Graphical Evaluation of Blood-to-Brain Transfer Constants from Multiple-Time Uptake Data. *Journal of Cerebral Blood Flow & Metabolism* **3**:1–7. doi:10.1038/jcbfm.1983.1

Patton JH, Stanford MS, Barratt ES. 1995. Factor structure of the barratt impulsiveness scale. *Journal of Clinical Psychology* **51**:768–774. doi:10.1002/1097-4679(199511)51:6<768::AID-JCLP2270510607>3.0.CO;2-1

Petzold J, Lee Y, Pooseh S, Oehme L, Beuthien-Baumann B, London ED, Goschke T, Smolka MN. 2019. Presynaptic dopamine function measured with [18F]Fluorodopa and L-DOPA effects on impulsive choice. *Scientific Reports* **9**:17927. doi:10.1038/s41598-019-54329-1

Piray P, Ouden D, E.m H, Schaaf VD, E M, Toni I, Cools R. 2017. Dopaminergic Modulation of the Functional Ventrodorsal Architecture of the Human Striatum. *Cerebral Cortex* **27**:485–495. doi:10.1093/cercor/bhv243

Rac-Lubashevsky R, Slagter HA, Kessler Y. 2017. Tracking Real-Time Changes in Working Memory Updating and Gating with the Event-Based Eye-Blink Rate. *Scientific Reports* **7**:2547. doi:10.1038/s41598-017-02942-3

Salami A, Garrett DD, Wåhlin A, Rieckmann A, Papenberg G, Karalija N, Jonasson L, Andersson M, Axelsson J, Johansson J, Riklund K, Lövdén M, Lindenberger U, Bäckman L, Nyberg L. 2019. Dopamine D2/3 Binding Potential Modulates Neural Signatures of Working Memory in a Load-Dependent Fashion. *Journal of Neuroscience* **39**:537–547. doi:10.1523/JNEUROSCI.1493-18.2018

Salami A, Rieckmann A, Karalija N, Avelar-Pereira B, Andersson M, Wåhlin A, Papenberg G, Garrett DD, Riklund K, Lövdén M, Lindenberger U, Bäckman L, Nyberg L. 2018. Neurocognitive Profiles of Older Adults with Working-Memory Dysfunction. *Cerebral Cortex* **28**:2525–2539. doi:10.1093/cercor/bhy062

Schönbrodt FD, Perugini M. 2013. At what sample size do correlations stabilize? *Journal of Research in Personality* **47**:609–612. doi:10.1016/j.jrp.2013.05.009

Sescousse G, Ligneul R, Holst RJ van, Janssen LK, Boer F de, Janssen M, Berry AS, Jagust WJ, Cools R. 2018. Spontaneous eye blink rate and dopamine synthesis capacity: Preliminary

evidence for an absence of positive correlation. *European Journal of Neuroscience* **47**:1081–1086. doi:10.1111/ejn.13895

Slagter HA, Davidson RJ, Tomer R. 2010. Eye-blink rate predicts individual differences in pseudoneglect. *Neuropsychologia* **48**:1265–1268. doi:10.1016/j.neuropsychologia.2009.12.027

Slagter HA, Georgopoulou K, Frank MJ. 2015. Spontaneous eye blink rate predicts learning from negative, but not positive, outcomes. *Neuropsychologia* **71**:126–132. doi:10.1016/j.neuropsychologia.2015.03.028

Smith CT, Wallace DL, Dang LC, Aarts E, Jagust WJ, D'Esposito M, Boettiger CA. 2015. Modulation of impulsivity and reward sensitivity in intertemporal choice by striatal and midbrain dopamine synthesis in healthy adults. *Journal of Neurophysiology* **115**:1146–1156. doi:10.1152/jn.00261.2015

Swart JC, Froböse MI, Cook JL, Geurts DE, Frank MJ, Cools R, Ouden HE den. 2017. Catecholaminergic challenge uncovers distinct Pavlovian and instrumental mechanisms of motivated (in)Action. *eLife* **6**:e22169. doi:10.7554/eLife.22169

Taylor JR, Elsworth JD, Lawrence MS, Sladek JR, Roth RH, Redmond DE. 1999. Spontaneous Blink Rates Correlate with Dopamine Levels in the Caudate Nucleus of MPTP-Treated Monkeys. *Experimental Neurology* **158**:214–220. doi:10.1006/exnr.1999.7093

Team RC. 2020. R: A language and environment for statistical computing.

Unsworth N, Robison MK, Miller AL. 2019. Individual differences in baseline oculometrics: Examining variation in baseline pupil diameter, spontaneous eye blink rate, and fixation stability. *Cognitive, Affective, & Behavioral Neuroscience* **19**:1074–1093. doi:10.3758/s13415-019-00709-z

van den Bosch R, Lambregts B, Määttä J, Hofmans L, Papadopetraki D, Westbrook A, Verkes R-J, Booij J, Cools R. 2022. Striatal dopamine dissociates methylphenidate effects on value-based versus surprise-based reversal learning. *Nature Communications* **13**:4962. doi:10.1038/s41467-022-32679-1

van der Schaaf ME, van Schouwenburg MR, Geurts DEM, Schellekens AFA, Buitelaar JK, Verkes RJ, Cools R. 2014. Establishing the Dopamine Dependency of Human Striatal Signals During Reward and Punishment Reversal Learning. *Cerebral Cortex* **24**:633–642. doi:10.1093/cercor/bhs344

van Holst RJ, Sescousse G, Janssen LK, Janssen M, Berry AS, Jagust WJ, Cools R. 2018. Increased Striatal Dopamine Synthesis Capacity in Gambling Addiction. *Biological Psychiatry*, Impulsivity: Mechanisms and Manifestations **83**:1036–1043. doi:10.1016/j.biopsych.2017.06.010

Van Slooten JC, Jahfari S, Theeuwes J. 2019. Spontaneous eye blink rate predicts individual differences in exploration and exploitation during reinforcement learning. *Scientific Reports* **9**:17436. doi:10.1038/s41598-019-53805-y

Westbrook A, Bosch R van den, Määttä JI, Hofmans L, Papadopetraki D, Cools R, Frank MJ. 2020. Dopamine promotes cognitive effort by biasing the benefits versus costs of cognitive work. *Science* **367**:1362–1366. doi:10.1126/science.aaz5891

Westbrook A, Ghosh A, van den Bosch R, Määttä JI, Hofmans L, Cools R. 2021. Striatal dopamine synthesis capacity reflects smartphone social activity. *iScience* **24**:102497. doi:10.1016/j.isci.2021.102497

Yarkoni T, Westfall J. 2017. Choosing Prediction Over Explanation in Psychology: Lessons From Machine Learning. *Perspectives on Psychological Science* **12**:1100–1122. doi:10.1177/1745691617693393

Zandbelt B. 2017. Slice Display. *figshare*. doi:10.6084/m9.figshare.4742866