Comparison of neural substrates of temporal discounting between youth with autism spectrum disorder and with obsessive-compulsive disorder

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Background. Autism spectrum disorder (ASD) and obsessive-compulsive disorder (OCD) share abnormalities in hot executive functions such as reward-based decision-making, as measured in the temporal discounting task (TD). No studies, however, have directly compared these disorders to investigate common/distinct neural profiles underlying such abnormalities. We wanted to test whether reward-based decision-making is a shared transdiagnostic feature of both disorders with similar neurofunctional substrates or whether it is a shared phenotype with disorder-differential neurofunctional underpinnings.

Methods. Age and IQ-matched boys with ASD (N = 20), with OCD (N = 20) and 20 healthy controls, performed an individually-adjusted functional magnetic resonance imaging (fMRI) TD task. Brain activation and performance were compared between groups.

Results. Boys with ASD showed greater choice-impulsivity than OCD and control boys. Whole-brain between-group comparison revealed shared reductions in ASD and OCD relative to control boys for delayed-immediate choices in right ventromedial/lateral orbitofrontal cortex extending into medial/inferior prefrontal cortex, and in cerebellum, posterior cingulate and precuneus. For immediate-delayed choices, patients relative to controls showed reduced activation in anterior cingulate/ventromedial prefrontal cortex reaching into left caudate, which, at a trend level, was more decreased in ASD than OCD patients, and in bilateral temporal and inferior parietal regions.

Conclusions. This first fMRI comparison between youth with ASD and with OCD, using a reward-based decision-making task, shows predominantly shared neurofunctional abnormalities during TD in key ventromedial, orbital- and inferior fronto-striatal, temporo-parietal and cerebellar regions of temporal foresight and reward processing, suggesting trans-diagnostic neurofunctional deficits.

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Key words: ASD, fMRI, OCD, temporal discounting.
Introduction

Autism Spectrum Disorder (ASD) is characterized by social communication difficulties and stereotyped repetitive behaviours (American Psychiatric Association, 2013) with a prevalence of 0.6–2%, predominantly in males (Blumberg et al. 2013). Obsessive-Compulsive Disorder (OCD) involves recurrent, intrusive and distressing thoughts (obsessions) and repetitive rituals (compulsions) (American Psychiatric Association, 2013), affecting 1–3% of the population with a higher male prevalence in children (Ruscio et al. 2010). These disorders are highly comorbid, with rates exceeding 30% (Simonoff et al. 2008) and can sometimes be clinically difficult to separate (Doshi-Velez et al. 2014).

The allowance of co-diagnosis of OCD with ASD in DSM-5 questions whether phenotypes common to both disorders are mediated by shared or disorder-specific mechanisms. Characteristic behaviours observed in ASD are wide-ranging and heterogeneous but can include physical rocking, tapping, counting and behavioural inflexibility (e.g. insistence on performing actions in a certain order). Similarly, behaviours in OCD vary widely, but compulsions often include hand-washing, checking, and, sometimes seemingly similar to ASD, counting and behavioural inflexibility surrounding order and symmetry. It has been hypothesized that in both cases, these behaviours may relate to abnormalities in fronto-striatal circuitry that is also important in reward-based decision-making (Langen et al. 2011). In ASD, repetitive behaviours are often considered soothing and rewarding, while in OCD, compulsions are performed to reduce anxiety and are often debilitating. However, despite this distinction, converging evidence suggests repetitive behaviours in ASD and OCD may be mediated by shared mechanisms including behavioural disinhibition or motivation control (Hollander et al. 2007). Such impairments may maintain diminished control over repetitive behaviours in ASD and compulsions in OCD and involve goal-directed reward-based decision-making. A meta-analysis of structural and functional neuroimaging studies comparing ASD and OCD found shared reduced structure and function during cognitive control in medial prefrontal regions but that OCD had disorder-specific increased function and structure in basal ganglia and insula while ASD had disorder-specific functional reduction in DLPFC and reduced PCC deactivation, presumably reflecting disorder-specific fronto-striato-insular dysregulation in OCD but fronto-striato-insular maldevelopment in ASD, both underpinned by shared reduced prefrontal control (Carlisi et al. 2016b).

Both disorders also share deficits in motivated ‘hot’ executive functions (EF) (Zelazo & Müller, 2007) including reward-based decision-making measured by choice-impulsivity tasks of gambling and temporal discounting (TD) (Hill, 2004; Sanders et al. 2008; Abramovich et al. 2013; Chen et al. 2016). TD requires choosing between small immediate rewards and larger later rewards, assessing the extent to which a reward is subjectively discounted when delayed in time (Rubia et al. 2009). The ability to inhibit immediate reward choices and wait for larger rewards depends on well-developed frontal lobe-mediated motivation control and temporal foresight and is a key for mature decision-making. A TD function is typically hyperbolic, with steeper rates reflecting more impulsive choice behaviour (Richards et al. 1999) (see online Supplement). TD matures with age (Christakou et al. 2011; Steinbeis et al. 2016) and varies among individuals (Odum, 2011), with steeper TD observed in younger people and individuals with attention deficit hyperactivity disorder (ADHD) and related impulsive disorders (Rubia et al. 2009; Noreika et al. 2013). Functional magnetic resonance imaging (fMRI) studies of TD in healthy adults and children implicate ventromedial-fronto-limbic networks of reward-based decision-making and dorsolateral and inferior-fronto-insula-striato-parietal networks of temporal foresight (Christakou et al. 2011; Chantiluke et al. 2014b; Wesley & Bickel, 2014).

People with ASD have been shown to have deficits in reward-motivated and forward-thinking behaviour including reward processing and reversal learning (Scott-Van Zeeland et al. 2010; Chantiluke et al. 2015a), incentive processing (Dichter et al. 2012), planning (Ozonoff & Jensen, 1999; Geurts et al. 2004; Hill, 2004) and TD (Chantiluke et al. 2014b). However, there have also been negative findings (Antrop et al. 2006; Demurie et al. 2013). ASD is characterized by fronto-temporo-limbic abnormalities mediating socio-emotional processes (Via et al. 2011; Philipp et al. 2012; Carlisi et al. 2016b), and in ventromedial/fronto-limbic brain regions involved in TD (Christakou et al. 2011; Peters & Büchel, 2011) during reward-related and planning tasks (Just et al. 2007; Schmitz et al. 2008; Dichter et al. 2012; Kohls et al. 2013). However, only one fMRI study has been published investigating the neural correlates of TD in adolescents with ASD, which found a weaker relationship between task-performance and bilateral superior temporal and right insular activation relative to controls (Chantiluke et al. 2014b).

Patients with OCD show deficits during planning (van den Heuvel et al. 2011; Shin et al. 2014), goal-directed learning (Gillan & Robbins, 2014; Voon et al. 2015), reward-based decision-making, gambling (Grassi et al. 2015; Figue et al. 2016), and incentive processing (Figue et al. 2011). Despite evidence that heightened impulsivity is a phenotype associated with OCD
(Benatti et al. 2014), only one (Sohn et al. 2014) of three TD studies in OCD (Vloet et al. 2010; Pinto et al. 2014; Sohn et al. 2014) found performance deficits.

Neuroimaging studies show that OCD is characterized by structural and functional abnormalities in medial and orbitofronto-striato-thalamo-cortical networks mediating EF (Menzies et al. 2008; Radua et al. 2010; Carlisi et al. 2016b; Norman et al. 2016). No fMRI studies, however, have investigated TD in OCD. Studies using other decision-making tasks in OCD have found hyperactivity in ventral-affective regions including ventromedial prefrontal, orbitofrontal and rostral anterior cingulate cortex (rACC) projecting to ventral striatum and mediiodorsal thalamus, and hypoactivity in dorsal-cognitive cortico-striato-thalamic regions including dorsolateral prefrontal (DLPFC), temporal and parietal association cortex projecting to the dorsal striatum and caudate in patients relative to controls (Menzies et al. 2008; Brem et al. 2012). Hypoactivation in DLPFC and caudate has furthermore been shown in OCD patients during planning (van den Heuvel et al. 2005, 2011).

This suggests that ASD and OCD have abnormalities during planning and ‘hot’ EF tasks including reward-based decision-making, and that this may be underpinned by ventromedial and dorsolateral prefronto-striato-limbic abnormalities. However, it is unclear whether reward-based decision-making problems in both disorders are underpinned by shared transdiagnostic mechanisms or by disorder-specific underlying abnormalities.

We hypothesized that adolescents with ASD would be more impaired on TD relative to adolescents with OCD and controls (Scott-Van Zeeland et al. 2010; Chantiluke et al. 2014b; Chen et al. 2016) and that both clinical groups compared with healthy controls would show underactivation in underlying ventromedial prefrontal, limbic and striatal regions mediating TD (Fineberg et al. 2009), reflecting a trans-diagnostic neurofunctional phenotype (Chantiluke et al. 2015a; Grassi et al. 2015; Chen et al. 2016). However, we hypothesized that people with OCD would show disorder-specific (ventromedial and dorsolateral-prefrontal dysfunction (Menzies et al. 2008; Carlisi et al. 2016b; Norman et al. 2016) while ASD adolescents would show disorder-specific insular and tempo-parietal dysfunction compared to controls (Di Martino et al. 2009; Chantiluke et al. 2014b; Carlisi et al. 2016b).

Methods

Participants

Sixty-nine right-handed (Oldfield, 1971) boys (20 controls, 29 boys with ASD, 20 boys with OCD), 11–17 years, IQ $\geq$ 70 (Wechsler, 1999) participated. Medication-naive boys with high-functioning ASD were recruited from local clinics and support-groups. ASD diagnosis was made by a consultant psychiatrist using ICD-10 research diagnostic criteria (WHO, 1992) and confirmed with the Autism Diagnostic Interview-Revised [ADI-R; (Lord et al. 1994)]. The ADI-R and the Autism Diagnostic Observation Schedule [ADOS; (Lord et al. 2000)] were completed for all ASD boys; all 29 reached autism cut-offs on all ADI-R (social/communication/restricted/sterotyped) and ADOS (communication/social) domains. ASD participants either fulfilled ICD-10 research diagnostic criteria for autism ($N=7$) or fulfilled these criteria but had no history of language delay and therefore were subtypep with Asperger’s syndrome ($N=22$). Parents of ASD boys completed the Social Communication Questionnaire [SCQ; (Rutter et al. 2003)] and the Strengths and Difficulties Questionnaire [SDQ; (Goodman & Scott, 1999)] (see online Supplement). ASD participants had a physical examination to exclude comorbid medical disorders and biochemical, haematological and chromosomal abnormalities associated with ASD. None of the ASD individuals had a comorbid diagnosis of OCD or any psychiatric disorder, and none of the OCD patients had comorbid ASD.

OCD boys were recruited from National and Specialist OCD clinics. Diagnosis was made by a consultant psychiatrist using ICD-10 criteria and confirmed by the Children’s Yale-Brown Obsessive-Compulsive Scale [CY-BOCS; (Goodman et al. 1989)]. Parents of OCD patients completed the SDQ. Patients with comorbid psychiatric or neurological disorders, including ASD, were not included in the OCD sample, although OCD patients were not specifically assessed for ASD. Four boys were prescribed stable doses of antidepressants (see online Supplement).

Twenty age and handedness-matched healthy controls were recruited locally by advertisement. Controls scored below clinical threshold on the SDQ and SCQ for any disorder and did not have any psychiatric condition.

Exclusion criteria for all participants included comorbid psychiatric or medical disorders affecting brain development (e.g. epilepsy/psychosis), drug/alcohol dependency, head injury, genetic conditions associated with ASD, abnormal structural brain scan and MRI contraindications. All controls also participated in previously published studies testing fluoxetine effects on TD in ADHD (Carlisi et al. 2016a) and neurofunctional maturation of TD in healthy adults and adolescents (Christakou et al. 2011); all but four ASD boys participated in our fMRI TD study comparing ASD and ADHD (Chantiluke et al. 2014b). Most ASD and control participants also participated in other fMRI tasks during their visit, published elsewhere (Christakou et al. 2013a, 2013b; Chantiluke et al. 2014a, 2015a, b; Murphy et al. 2014).
This study was conducted in accordance with the Declaration of Helsinki. Ethical approval was obtained from the local Research Ethics Committee (05/Q0706/275). Study details were explained to child and guardian, and written informed consent was obtained for all participants.

**TD paradigm**

Prior to scanning, subjects practiced the 12-min TD task (Rubia et al. 2009; Christakou et al. 2011; Chantiluke et al. 2014b) in a mock-scanner. Subjects chose by pressing a left/right button with right index/middle-finger between receiving a small amount of money immediately (£0–£100) or receiving £100 in 1 week, month or year (Fig. 1). Delays (20 trials each) were randomized, but the delayed option (£100) was consistently displayed on the right side of the screen, and variable immediate choices on the left, minimizing sensorimotor mapping effects. Choices were displayed for 4 s, followed by a blank screen of at least 8 s (inter-trial-interval: 12 s). The immediate reward amount was adjusted through an algorithm based on previous choices and calculated separately for each delay. This narrows the range of values, converging on an indifference point where the immediate reward is subjectively considered equivalent to the delayed amount for the given delay (Rubia et al. 2009), ensuring comparable numbers of immediate and delayed choices for analysis.

**Analysis of performance data**

To estimate TD steepness for each subject, indifference values between the immediate amount and delayed £100 for each delay were calculated, equal to the participant’s subjective value of £100 after each delay and defined as the midpoint between the lowest chosen immediate reward and the next lowest immediate reward available (i.e. the value of the immediate reward offered at which point the subject began to choose the delayed reward) (Christakou et al. 2011).

TD was measured using area under the curve (AUC) (Myerson et al. 2001). Smaller AUC denotes steeper discounting rates (i.e. increased choice-impulsivity) (see online Supplement).

One-way between-group analysis of variance (ANOVA) was conducted with AUC as dependent measure to examine group-differences.

**fMRI image acquisition**

Gradient-echo echo-planar imaging (EPI) data were acquired at King’s College London on a 3T-General...
Electric SIGNA HDx MRI scanner (Milwaukee, WI) using the body coil for radio frequency transmission and a quadrature birdcage head coil for reception. See online Supplement for acquisition parameters. Total scan was 1.5 h during which subjects completed 2–3 additional fMRI tasks.

**fMRI image analysis**

Event-related data were acquired in randomized trial presentation and analysed using the non-parametric XBAM package (v4.1) [www.brainmap.co.uk; (Brammer et al. 1997)]. The individual and group-level analysis methods are described in detail elsewhere (Brammer et al. 1997; Bullmore et al. 1999b; Cubillo et al. 2014) and in the online Supplement.

Briefly, fMRI data were realigned to minimize motion-related artefacts and smoothed using a 7.2 mm full-width-at-half-maximum (FWHM) Gaussian filter (Bullmore et al. 1999a). Time-series analysis of individual activation was performed with a wavelet-based resampling method (Bullmore et al. 2001). The main experimental conditions were convolved with 2 Poisson model functions (peaking at 4 and 8 s). The weighted sum of these convolutions giving the best fit (least-squares) to the time series at each voxel was calculated. A goodness-of-fit statistic (SSQ ratio) was then computed at each voxel consisting of the ratio of the sum of squares of deviations from the mean intensity value due to the model (fitted time series) divided by that of the squares due to the residuals (original minus model time series). This statistic, the SSQ ratio, was used in further analyses. Individual maps were then normalised to Talairach space (Talairach & Tournoux, 1988), and a group activation map was produced for each group.

**ANCOVA of between-group effects**

One-way between-group analysis of covariance (ANCOVA) with age as covariate was conducted using randomization-based testing to investigate case-control differences (Bullmore et al. 1999b, 2001). For these comparisons, statistical thresholds of 0.05 (voxel-level)/0.015 (cluster-level) were selected to obtain <1 false-positive 3D cluster per map. Standardized blood-oxygenation level-dependent (BOLD) responses were extracted from significant clusters for each participant and plotted to determine effect direction. Post-hoc significance was determined among pairwise comparisons using a one-way ANOVA.

**Influence of behaviour, symptoms and medication**

To examine whether clusters showing significant group effects were related to TD performance or symptoms, BOLD response from these clusters was extracted for each participant and Spearman correlations (two-tailed) were performed with AUC and symptom subscales within each group. FMRI analyses were also repeated including AUC as covariate.

Lastly, analyses were repeated excluding the four OCD participants prescribed medication.

**Results**

**Participants**

There were no significant group-differences in age and IQ (Table 1). Multivariate ANOVAs showed group-differences on SDQ scores; Post-hoc tests revealed that patients had higher total-scores than controls, with ASD being more impaired than OCD patients (all \( p < 0.001 \)). On the emotional-distress subscale, both patient groups were more impaired than controls (\( p < 0.001 \)) but did not differ from each other. On all other SDQ subscales, ASD patients were significantly more impaired than controls and OCD patients (all \( p < 0.005 \)), who did not differ on any measure, with the exception of the conduct subscale where ASD patients differed from controls only (\( p < 0.001 \)).

**Performance**

AUC correlated inversely with \( k \) (as measured by the square-root transform of these values: \( r = -0.555, \ p < 0.001 \)), suggesting adequate congruency between these two metrics. AUC differed between groups [controls: \( 0.56 \pm 0.13 \); ASD: \( 0.45 \pm 0.24 \); OCD: \( 0.59 \pm 0.15 \); \( F(2,66) = 4.04, \ p = 0.02 \)]. Post-hoc comparisons showed that ASD patients had significantly smaller AUC compared with controls (\( p < 0.05 \)) and OCD patients (\( p < 0.01 \)), indicating ASD patients discounted rewards more steeply than the other groups, who did not differ from each other.

**fMRI data**

**Movement**

Multivariate ANOVA showed no group-differences in mean head rotation \([F(2,66) = 1.17, \ p = \text{n.s.}]\) or translation \([F(2,66) = 2.59, \ p = \text{n.s.}]\) in 3-dimensional Euclidian space.

**Group maps of brain activation for delayed-immediate choices**

See online Supplement for maps of brain activation within each group for the contrast of delayed-immediate choices (online Supplementary Fig. S1).
**Table 1. Participant characteristics for healthy control boys and patients with OCD or ASD**

<table>
<thead>
<tr>
<th>Variables</th>
<th>HC (N = 20) Mean (s.d.)</th>
<th>ASD (N = 29) Mean (s.d.)</th>
<th>OCD (N = 20) Mean (s.d.)</th>
<th>F test (df)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>15.29 (1.8)</td>
<td>14.72 (1.8)</td>
<td>15.74 (1.4)</td>
<td>2.22 (2,66)</td>
<td>0.12</td>
</tr>
<tr>
<td>IQ</td>
<td>118.90 (11.9)</td>
<td>113.17 (13.1)</td>
<td>117.70 (13.4)</td>
<td>1.38 (2,66)</td>
<td>0.26</td>
</tr>
<tr>
<td>SCQ total score</td>
<td>2.32 (2.3)</td>
<td>18.66 (8.1)</td>
<td>–</td>
<td>76.98 (1,47)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SDQ total score</td>
<td>5.58 (4.2)</td>
<td>19.66 (6.8)</td>
<td>12.45 (5.6)</td>
<td>35.56 (2,66)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SDQ emotional distress subscale</td>
<td>0.93 (1.8)</td>
<td>4.38 (2.9)</td>
<td>4.35 (2.6)</td>
<td>13.12 (2,66)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SDQ conduct subscale</td>
<td>0.86 (1.1)</td>
<td>2.69 (2.2)</td>
<td>1.85 (1.5)</td>
<td>6.55 (2,66)</td>
<td>0.003</td>
</tr>
<tr>
<td>SDQ peer relations subscale</td>
<td>1.53 (1.7)</td>
<td>6.59 (2.3)</td>
<td>3.30 (3.0)</td>
<td>28.72 (2,66)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SDQ hyperactive impulsive/inattentive subscale</td>
<td>2.72 (2.4)</td>
<td>5.93 (2.6)</td>
<td>2.95 (2.7)</td>
<td>12.52 (2,66)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SDQ prosocial behaviour subscale</td>
<td>8.38 (2.4)</td>
<td>4.41 (2.4)</td>
<td>7.65 (2.6)</td>
<td>18.61 (2,66)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ADOS communication score</td>
<td>–</td>
<td>3.62 (1.2)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ADOS social interaction score</td>
<td>–</td>
<td>9.03 (2.3)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ADOS communication + social</td>
<td>–</td>
<td>12.66 (3.1)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ADOS stereotypy score</td>
<td>–</td>
<td>1.52 (1.5)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ADI communication score</td>
<td>–</td>
<td>16.59 (4.7)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ADI social interaction score</td>
<td>–</td>
<td>19.97 (5.3)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ADI repetitive behaviour score</td>
<td>–</td>
<td>6.45 (2.4)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CY-BOCS total score</td>
<td>–</td>
<td>–</td>
<td>22.33 (5.8)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CY-BOCS – obsessions</td>
<td>–</td>
<td>–</td>
<td>10.79 (3.6)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CY-BOCS – compulsions</td>
<td>–</td>
<td>–</td>
<td>12.01 (3.1)</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

AD1, autism diagnostic interview; ADOS, autism diagnostic observation schedule; ASD, autism spectrum disorder; CY-BOCS, Children’s Yale-Brown obsessive-compulsive symptoms checklist; HC, healthy controls; OCD, obsessive-compulsive disorder; SCQ, social communication questionnaire; SDQ, strengths and difficulties questionnaire.

**Group-effects on brain activation**

One-way ANOVA showed a significant group-effect for delayed-immediate choices in right ventromedial orbitofrontal cortex (vmOFC) extending into MPFC/lateral OFC/inferior frontal cortex (IFC), in cerebellum extending into occipital lobe/posterior cingulate (PCC)/precuneus, in rACC/vmPFC extending into left caudate, in left superior/middle temporal lobe (STL/MTL)/inferior parietal lobe (IPL) and in right MTL/STL extending into posterior insula/postcentral gyrus/IPL (Fig. 2a; Table 2). ANCOVA including AUC as covariate showed that effects in rACC/vmPFC and PCC/precuneus were related to task performance.

Post-hoc analyses based on extracted SSQs showed that abnormalities in vmOFC/MPFC/IFC were shared between OCD and ASD patients, who had increased activation to immediate-delayed choices relative to controls (both p < 0.001), who had more activation to delayed choices. In cerebellum/occipital lobe/PCC/precuneus, ASD and OCD patients had reduced activation to delayed-immediate choices compared with controls (both p < 0.001). In rACC/vmPFC/caudate, both patient groups had decreased activation to immediate-delayed choices relative to controls (ASD: p < 0.001; OCD: p < 0.05), who had enhanced activation to immediate-delayed choices, but this effect was more pronounced in ASD v. OCD patients at trend-level (p < 0.1).

Findings in right MTL/STL/insula/postcentral gyrus/IPL (all p < 0.005) and left STL/MTL/IPL were due to shared abnormalities in ASD (p < 0.001) and OCD (p < 0.005) patients, who had less activation to immediate-delayed choices relative to controls who activated this region for immediate v. delayed choices (Fig. 2b). When the four OCD patients prescribed medication were excluded from analyses, main findings remained, suggesting medication did not influence task-related activation.

**Correlations between differentially activated brain regions and performance**

Correlations between areas that differed between groups and AUC showed that greater activation to delayed-immediate choices in cerebellum/occipital lobe/PCC/precuneus was correlated with less-steepest TD in the ASD (r = 0.66, p < 0.001) and OCD groups (r = 0.45, p < 0.05). Greater activation to immediate-delayed choices in left STL/IPL correlated with less-steepest TD performance in the ASD group (r = −0.41, p < 0.05). In right MTL/STL/insula/postcentral gyrus/IPL, it correlated with better TD performance in both ASD (r = −0.39, p < 0.05) and OCD (r = −0.59, p < 0.005).
Fig. 2. Between-group activation differences for delayed minus immediate choices. (a) Axial slices showing split-plot analysis of variance (ANOVA) effects of group on brain activation to delayed – immediate choices. Talairach Z coordinates are indicated for slice distance (in mm) from the intercommissural line. The right side of the image corresponds to the right side of the brain. (b) Extracted statistical measures of BOLD response are shown for each of the three groups for each of the brain regions that showed a significant group effect. Black asterisks indicate a significant difference between controls and patient group. Red asterisk indicates a difference between the two patient groups. (*) = significant at a trend level; * = significant at the $p < 0.05$ level; ** = significant at the $p \leq 0.005$ level; *** = significant at the $p \leq 0.001$ level.
Correlations between differentially activated brain regions and symptoms

In ASD boys, greater activation to delayed v. immediate choices in right vmOFc/MPFC/lateral OFC/IFC correlated at trend-level with lower symptom severity on the repetitive behaviour subscale of the ADI-R ($r = -0.34$, $p = 0.07$). In bilateral STL/insula, lower repetitive behaviour symptom severity was related to increased activation to immediate-delayed choices in the ASD group ($l e f t r = 0.47$, $p < 0.01$; $r i g h t r = 0.42$, $p < 0.05$). In the OCD group, increased activation to delayed v. immediate choices in cerebellum/occipital lobe/PCC/precuneus correlated with lower symptom severity on the CY-BOCS compulsions subscale ($r = -0.58$, $p < 0.01$). There were no correlations between activation and other subscales from the CY-BOCS in OCD or ADOS/ADI-R in ASD.

Discussion

This comparison between ASD and OCD adolescents on a ‘hot’ EF measure of decision-making showed disorder-specific impaired TD in ASD relative to OCD boys and controls. Despite this, patients had predominantly shared neurofunctional deficits in key TD areas including vmOFc/MPFC/lateral OFC/IFC, bilateral temporoparietal and cerebellar regions, suggesting that the neural basis of TD is a trans-diagnostic feature of both disorders. In ACC/vmPFC extending into caudate, ASD boys had trend-level more severe underactivation relative to OCD and controls for immediate v. delayed choices.

Disorder-specific performance impairment in ASD relative to OCD boys extends previous findings of impairments in ASD during TD (Chantiluke et al. 2014b), although there have been negative findings (Demurie et al. 2012). The absence of performance differences between OCD boys and controls is in line with previous studies (Vloet et al. 2010; Pinto et al. 2014) [but see (Sohn et al. 2014)]. Moreover, ASD boys had elevated scores on the hyperactive-impulsive/inattention subscale of the SDQ compared with OCD boys and controls. The disorder-specific performance impairment in the ASD group may relate to these elevated impulsivity symptoms observed in ASD but not OCD, given that ADHD patients are consistently impaired in TD (Jackson & MacKillop, 2016). This finding exclusive to ASD lends support to the distinction between impulsive and compulsive behaviours (Robbins et al. 2012), suggesting that while both disorders exhibit deficits in top-down cognitive control and related circuitry (Dalley et al. 2011), ASD individuals exhibit more impulsive decision-making during TD, as evidenced by disorder-specific impairments and possibly supported by trend-level disorder-specific abnormalities in ACC/vmPFC/caudate, while OCD patients are more habitually compulsive, supported by intact choice behaviour and no disorder-specific abnormalities.

Both patient groups had reduced activation relative to controls to delayed-immediate choices in ventromedial and ventrolateral OFC/IFC. Ventromedial and ventrolateral fronto-limbic regions are key temporal foresight areas (Christakou et al. 2011; Peters & Büchel, 2011) thought to support calculation of discounted reward value. Moreover, right IFC is a key region for working memory, attention to time and integration of external information with internal value representations, supporting goal-directed EF and mediation of temporal foresight (Wittmann et al. 2007; Rubio et al. 2009; Carlisi et al. 2016a) and has previously been shown to be abnormal during reward-related decision-making in both OCD (Bari & Robbins, 2013; Stern & Taylor, 2014) and ASD (Dichter et al. 2012; Kohls et al. 2013).

Both patient groups showed reduced activation in PCC/precuneus/occipital lobe/cerebellum to delayed-

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**Table 2.** Between-group activation differences for delayed minus immediate choices

<table>
<thead>
<tr>
<th>Brain regions of activation difference</th>
<th>Brodmann area (BA)</th>
<th>Peak Talairach coordinates ($x, y, z$)</th>
<th>Voxels Cluster $p$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) HC &gt; OCD, ASD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R vmOFc/MPFC/lateral OFC/IFC</td>
<td>47/11/25/10/46</td>
<td>40, 56, −13</td>
<td>189, 0.009</td>
</tr>
<tr>
<td>PCC/precuneus/occipital lobe/cerebellum</td>
<td>31/7/19/18/17</td>
<td>−14, −89, 4</td>
<td>1060, 0.0003</td>
</tr>
<tr>
<td>(B) OCD, ASD &gt; HC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rACC/vmPFC/left caudate</td>
<td>10/32/24</td>
<td>0, 41, 4</td>
<td>137, 0.01</td>
</tr>
<tr>
<td>L STL/MTL/IPL</td>
<td>22/39/40/7/19</td>
<td>−51, −56, 9</td>
<td>273, 0.005</td>
</tr>
<tr>
<td>R MTL/STL/posterior insula/postcentral gyrus/IPL</td>
<td>22/39/19/5/3/1/2/4/40/7</td>
<td>61, −22, 9</td>
<td>654, 0.001</td>
</tr>
</tbody>
</table>

ASD, autism spectrum disorder; HC, healthy controls; IFC, inferior frontal cortex; IPL, inferior parietal lobe; L, left; MTL, middle temporal lobe; OCD, obsessive-compulsive disorder; OFC, orbitofrontal cortex; R, right; STL, superior temporal lobe; rACC, rostral anterior cingulate cortex; vmOFc, ventromedial orbitofrontal cortex; vmPFC, ventromedial prefrontal cortex.
immediate choices compared with controls. These areas are important parts of fronto-limbic-parieto-cerebellar networks involved in motivation, reward evaluation and reward response (Vogt et al. 1992; McCoy et al. 2003). The cerebellum is typically activated during delayed choices in healthy populations and has been associated with future outcome expectancy and temporal bridging (Smith et al. 2003; Wittmann et al. 2007, 2010; Rubia et al. 2009; Christakou et al. 2011; Peters & Büchel, 2011; Noreika et al. 2013). We previously found similar effects in ADHD patients relative to controls during the same task, suggesting that cerebellar underactivation may be a trans-diagnostic feature of disorders that are challenged in TD (Rubia et al. 2009). Moreover, given the aforementioned role of fronto-limbic-parieto-temporo-cerebellar networks in motivation and reward evaluation, shared abnormalities in this network could possibly relate to neurofunctional similarities in the motivational and reward salience of e.g. performing repetitive behaviours in each disorder, in line with theories of shared impairments in motivation control underpinning these behaviours in each disorder (Hollander et al. 2007). This collectively provides first evidence for shared functional abnormalities in ventromedial and ventrolateral fronto-parieto-striato-cerebellar regions between ASD and OCD.

Conversely, relative to controls, both patient groups had reduced activation to immediate choices in the rACC/vmPFC reaching into caudate. However, these abnormalities were at trend-level more pronounced in ASD relative to OCD, possibly linking to ASD-specific performance impairments. rACC mediates decision conflict (Pochon et al. 2008) and typically is increased in activation with decision difficulty during intertemporal choice (Pine et al. 2009). Our recent meta-analysis of structural and functional MRI studies also found shared reductions in this region in ASD and OCD relative to controls both in volume and in activation during cognitive control (Carlisi et al., 2016b). In this study, however, we find that this dysfunction was trend-wise more impaired in ASD, implying a gradual rather than dichotomous effect of more severe impairment in ASD.

Findings of shared reduced vmPFC, left caudate, posterior insula and STL/IPL activation during immediate v. delayed choices in patients relative to controls are in line with evidence of abnormal impairments in these regions in temporal foresight and reward-based decision-making as well as possible abnormal maturation of networks mediating these processes in ASD and OCD. We showed previously that vmPFC activation to immediate choices during TD increases with age and AUC, indicating an increase in delay-tolerant behaviour linked to increased limbic-corticostrial activation with age (Christakou et al. 2013a). In children and adults, steeper TD has been associated with an imbalance between reduced activation in ventro-medial prefrontal and lateral frontal systems mediating evaluation of future reward and temporal foresight, and reduced top-down control over ventral-striatal and limbic systems, which respond to immediate reward (Christakou et al. 2011; Peters & Büchel, 2011; Chantiluke et al. 2014b). Moreover, tasks indexing vmPFC functioning have shown age-dependent increases in sensitivity to future consequences (Crone & van der Molen, 2004) and behavioural control during TD (Steinbeis et al. 2016).

The caudate is involved in time discrimination (Smith et al. 2003), has been linked to reward expectation and evaluation (Hinvest et al. 2011) and is activated during immediate choices in healthy individuals (Christakou et al. 2011). In OCD, OFC-caudate loops are proposed to drive impulsivity as well as compulsive behaviour (Fineberg et al. 2009; Dalley et al. 2011). Thus, results could suggest that adolescents with ASD and OCD both have problems with context-dependent decision-making but that this is more problematic for people with ASD, potentially relating to the findings of disorder-specific behavioural deficits in the ASD group. Moreover, the posterior insula is associated with decision-making in the context of prior risk (Xue et al. 2010) and is important for the integration of temporal-affective information (Elliott et al. 2000) and temporal encoding (Wittmann et al. 2010). While previous studies have found specifically anterior insula activation during TD in children (Rubia et al. 2009) and adults (Tanaka et al. 2004; Bickel et al. 2009; Hinvest et al. 2011), the present results highlight a differential abnormality in the posterior insula during reward presentation and internal state evaluation (Elliott et al. 2000) shared between ASD and OCD.

Findings of reduced activation to immediate-delayed choices in STL/IPL in ASD relative to controls are in line with evidence of weaker brain-behaviour correlations in this region in ASD relative to controls during TD (Chantiluke et al. 2014b) and extend these findings to OCD. These regions are important for temporal coding and reward selection (Cardinal, 2006; Christakou et al. 2011), suggesting deficits with planning, consistent with behavioural deficits in this domain in ASD (Hill, 2004) and OCD (Shin et al. 2014). IPL is specifically sensitive to delay (Rubia et al. 1998) and attention-allocation to time (Ortuno et al. 2002; Coulou, 2004; Rubia, 2006), as well as duration encoding (Wittmann, 2009) and quantity representation, which may contribute to inter-temporal choices regarding the IPL’s role in comparing time and value (Sandrini et al. 2004). Correlations between enhanced activation to immediate choices in the
patient groups and better TD performance suggest that in both groups, this upregulation is related to a shift in performance towards that of controls, providing possible mechanistic implications of this region in the context of TD behaviour. Moreover, increased activation bilaterally in this region in the ASD group correlated with lower levels of repetitive behaviours, linking performance improvement and symptom reduction to brain activation in these individuals, further highlighting the mechanistic implications of this region in the context of repetitive behaviours and decision-making.

Clinically, the fact that these disorders exhibit shared neural abnormalities during TD has implications for identification of common mechanisms, which may drive overlapping behaviours in each disorder. While symptoms such as compulsions in OCD can sometimes appear similar to repetitive behaviours in ASD at an observational level, less is known about the mechanistic underpinnings of these behaviours and related cognitive functions and whether they are shared or disorder-specific. Thus, this evidence sheds light on trans-diagnostic phenotypes that could aid in future treatment targets and work toward providing a biological explanation of commonalities and differences in clinical behaviour. This has similarly been shown in the case of inhibitory control and brain structure/function differences/similarities in a recent meta-analysis comparing ASD and OCD (Carlisi et al. 2016), and this study extends this understanding to temporal foresight and decision-making.

This study’s strengths include the thoroughness with which ASD individuals were assessed for the presence of ASD-related symptomatology and the exclusion of patients with psychiatric comorbidities. However, sub-threshold symptoms may have been present in the patient samples. The group of ASD patients tested in this study had a relatively high IQ, comparable with that of controls. While matching groups for IQ is important for fMRI studies to disentangle the effects of ASD from the effects of low IQ, this also means that the findings are not generalizable to other more typical ASD patients with low IQ (Charman et al. 2011; Crespi, 2016). The fact that most patients had high-functioning Asperger’s syndrome further limits generalizability. Thus, it is possible that OCD-related symptoms were present in the ASD sample and could account for some of the neurobiological overlap in results. In addition, sub-clinical levels of ASD-related symptoms may have been present in the OCD sample, as reflected by shared impairments compared with controls on the emotional-distress SDQ subscale. It would also be interesting to examine the possible effects of puberty on any observed abnormalities. However, it has been shown that impulsive behaviour is independent of puberty in males (Steinberg et al. 2008). Additionally, four OCD patients were prescribed antidepressant medication. While there is evidence for effects of serotonin on brain function (Murphy et al. 2008; Murphy, 2010), results remained when analyses were repeated excluding these patients. Lastly, It is a common finding that brain activation is more sensitive than performance to detect differences between groups in these patient groups (Fitzgerald et al. 2010; Duerden et al. 2013; Ambrosino et al. 2014; Marsh et al. 2014; Chantiluke et al. 2015b; Morein-Zamir et al. 2015). While the subject numbers have been shown to be sufficient for fMRI analyses (Thirion et al. 2007), the performance and correlation analyses, however, were underpowered.

Conclusions
This is the first study to compare brain function between these disorders and provides novel evidence to suggest that ASD and OCD share trans-diagnostic abnormalities during TD in ventromedial and ventrolateral fronto-striatal and fronto-temporo-parieto-cerebellar regions important for temporal foresight and reward-related decision-making. This may drive shared problems with reward-related behaviours and delaying repetitive actions.

Supplementary material
The supplementary material for this article can be found at https://doi.org/10.1017/S0033291717001088.

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Declaration Interest
K. R. has received funding from Lilly for another project and speaker’s honoraria from Lilly, Shire, Novartis.
and Medice. D. M. has received funding for another project from Lilly. M. B. has served as a consultant for PIVital. The other authors have no conflict of interests to declare.

Ethical standards

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

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