Neural correlates of preferred activities: development of an interest-specific go/nogo task

Dienke J. Bos,1,2 Eliana L. Ajodan,1,3 Melanie R. Silverman,1,3 Jonathan P. Dyke,4 Sarah Durston,2 Jonathan D. Power,1,5 and Rebecca M. Jones1,3

1Weill Cornell Medicine, The Sackler Institute for Developmental Psychobiology, Department of Psychiatry, New York, NY, USA, 2Department of Psychiatry, Brain Center Rudolf Magnus, University Medical Center Utrecht, Utrecht University, Utrecht, The Netherlands, 3Weill Cornell Medicine, Center for Autism and the Developing Brain, Department of Psychiatry, New York, NY, USA, 4Weill Cornell Medicine, Citigroup Biomedical Imaging Center, Department of Radiology, New York, NY, USA, and 5Department of Psychiatry, New York Presbyterian Hospital, NY, USA

Correspondence should be addressed to Dienke J. Bos, The Sackler Institute for Developmental Psychobiology, Department of Psychiatry, Weill Cornell Medicine, Box 140, 1300 York Avenue, New York, NY 10065, USA. E-mail: dienkebos@gmail.com

Abstract

The activities we choose to spend our leisure time with are intrinsically motivating and vary across individuals. Yet it is unknown how impulse control or neural activity changes when processing a preferred stimulus related to a hobby or interest. Developing a task that assesses the response to preferred interests is of importance as it would be relevant to a range of psychiatric disorders that have hyper- or hypo-arousal to such cues. During functional Magnetic Resonance Imaging (fMRI), 39 healthy adults completed a novel task to test approach behavior and cognitive control to cues that were personalized to the participants' interests compared to stimuli the participants identified as being of non-interest and colored shapes. fMRI results showed that cues of one's interest elicited activation in the anterior insula compared to colored shapes. Interests did not change inhibition compared to non-interests and colored shapes and all stimuli equally engaged a frontostriatal circuit. Together the results suggest that adults were sensitive to their interests but were effective at regulating their impulses towards these cues, a skill that is critical for navigating the temptations and distractions in our daily environment.

Key words: motivational cues; interests; impulse control; go/nogo task; fMRI; anterior insula

Introduction

Motivation drives human behavior and decision-making. A large body of work shows that affective or rewarding stimuli such as faces, erotic images, food images and money can bias decision making and that individuals often have difficulty exerting cognitive control over their responses to these cues (Somerville et al., 2011; Tottenham et al., 2011; Geier and Luna, 2012; Demos et al., 2012; Deuter et al., 2013; Teslovich et al., 2014). However, it is unknown how behavior or neural activity changes when processing stimuli related to one's preferred activities. Unlike money or social cues which are fundamental motivators (Daw and Doya, 2006; Jones et al., 2011), individuals may differ in how they choose to spend their leisure time or what professional career they pursue, suggesting that certain hobbies or interests may be more intrinsically motivating to certain individuals. Intriguingly, individuals with Major Depressive Disorder often express less interest in engaging in leisure activities of all kinds...
and conversely individuals with Autism Spectrum Disorder (ASD) often have an intense focus on a specific hobby or interest that disrupts daily functioning (American Psychiatric Association, 2013). Thus, understanding the typical response to stimuli relating to preferred activities and whether there are differences in cognitive control when presented with these stimuli may provide a foundation that ultimately can be applied to studying a range of disorders that demonstrate either hypo- or hyper- arousal to such stimuli.

Using various response inhibition paradigms, including go/no-go tasks, prior work has shown that accuracy (hit rate) and reaction times vary depending on the motivational content of stimuli. For example, healthy adults were faster to respond to stimuli relating to preferred activities and whether there are differences. Using personalized interests may be particularly relevant as approaches to cues that reflected one’s interests is still unknown.

A network of brain areas that has been associated with the identification of relevant or motivating stimuli is the ‘salience network’, including the dorsal Anterior Cingulate Cortex (dACC) and the bilateral insula (Seeley et al., 2007). The latter is broadly implicated in the processing of a wide range of affective stimuli including both positive and negative emotional faces and scenes. Specifically, processing positive stimuli demonstrated left dominance in anterior insula activity (for a comprehensive overview and meta-analysis, see Duerden et al., 2013). In addition to detecting positive valence, the insula is thought to be closely tied to cognitive control, where this region may be crucial in initiating modulation of frontostrital control areas (Dosenbach et al., 2006; Menon and Uddin, 2010; Jiang et al., 2015). Together these findings suggest the importance of the anterior insula in affective processing and promoting flexible cognitive control abilities.

Response inhibition tasks with specific, motivating stimuli have also provided deeper insight into the mechanisms of various psychiatric disorders. For example, food, non-food and physical activity cues have been used to study eating disorders (Brooks et al., 2011; Kullmann et al., 2014; Teslovich et al., 2014), pictures of alcohol, drugs or gambling to study various addictions (Noël et al., 2007; van Holst et al., 2012; Pike et al., 2013, 2015), and positive (happy) and negative (sad or threat) facial expressions or words to study mood disorders and schizophrenia (Elliott et al., 2004; Erickson et al., 2005; Wessa et al., 2007; Hummer et al., 2013; Krakowski et al., 2016). There are currently no go/no-go tasks that utilize cues that reflect individual preferences. Using personalized interests may be particularly relevant to psychiatric disorders such as ASD or Major Depressive Disorder.

We developed a novel neuroimaging paradigm to test approach behavior and cognitive control to cues that reflected participants’ preferences compared to stimuli that participants identified as non-interests. Participants performed the task during functional Magnetic Resonance Imaging (fMRI) to determine changes in blood oxygenation linked to accompanying neural activity. Participants also completed a well-established affective go/no-go paradigm, using facial expressions, where we expected to find results typical for this task (Hare and Casey, 2005; Shafritz et al., 2006; Schulz et al., 2007). The social stimuli served as a comparison condition to the non-social stimuli in the interests conditions. We predicted that participants would have faster reaction times to their interests and would be more impulsive to these cues compared to their non-interests. We predicted these behavioral findings would be associated with increased activity in arousal circuitry, including anterior insula. We also predicted that successful inhibition to these cues would engage increased activity in cognitive control regions such as the inferior frontal gyrus (IFG) (Aron et al., 2014). Lastly, we explored whether healthy adults with more ASD-like traits or greater impulsivity (e.g. Attention Deficit Hyperactivity Disorder (ADHD)-like traits) would demonstrate increased sensitivity to cues of their interest.

### Materials and methods

#### Participants

Forty healthy adults (22 males, 18 females), aged 18–29 years (Table 1) were recruited to participate through the Sackler Institute for Developmental Psychobiology in Manhattan, New York. All participants reported no use of psychotropic medications, past diagnoses of, or treatment for, psychiatric or neurological disorders. Participants were right-handed except for one individual, as measured by the Physical And Neurological Examination for Soft Signs (Table 1, PANESS: (Denckla, 1985)). Informed written consent was obtained from all participants as approved by the Weill Cornell Medicine Institutional Review Board.

#### Cognitive testing and self-report questionnaires

Participants completed the Wechsler Adult Intelligence Scale (WAIS-IV) (Wechsler, 2008) so that each individual had standard scores for verbal and non-verbal IQ (Table 1). In addition, to measure general ASD symptoms, participants completed the Social Responsiveness Scale (SRS-2) (Constantino, 2012) and the Autism Quotient (AQ) (Baron-Cohen et al., 2001). Individuals

| Demographics | Participants |
|--------------|--------------|
| Age—Mean ± SD | 23.6 ± 3.3 |
| Gender (M/F) | 22/18 |
| Handedness (right/left/ambidextrous) | 39/0/1 |

| Cognitive abilities | Participants |
|--------------------|--------------|
| VIQ—Mean ± SD | 110.8 ± 16.6 |
| NVIQ—Mean ± SD | 103.4 ± 17.1 |

| Self-Report Questionnaires | Participants |
|-----------------------------|--------------|
| SRS T-score—Mean ± SD | 53.8 ± 9.1 |
| AQ—Mean ± SD | 16.9 ± 7.2 |
| ASR Attention problems T-score—Mean ± SD | 53.6 ± 6.8 |
| ASR ADHD T-score—Mean ± SD | 53.4 ± 5.6 |

**Abbreviations:** ADHD – Attention Deficit/Hyperactivity Disorder, ASR – Adult Self-Report, AQ – Autism Quotient, NVIQ – non-verbal intelligence quotient, SD – standard deviation, SRS – Social-Responsiveness Scale-2, VIQ – verbal intelligence quotient.
traits such as impulsivity and hyperactivity. (ASR: Achenbach and Rescorla, 2003) to measure ADHD-like analyses. Participants also completed the Adult Self Report (ASR: Achenbach and Rescorla, 2003) to measure ADHD-like traits such as impulsivity and hyperactivity.

Experimental task

Outside of the MRI scanner, participants were presented with images of 23 popular hobbies or activities such as cooking, sports, hiking, subway maps, Japanese anime or trucks and were asked to choose their favorite interest or hobby and their least favorite from the options. The 23 options were based upon prior informal polling of common adult interests or hobbies as well as common interests for individuals with ASD (Klin et al., 2007) (described in detail in the Supplementary Material). Participants confirmed their preference and dislike by rating their choices on a 10-point rating scale and interests were rated as more pleasurable than non-interests \( t(39) = 15.6, P < .001 \).

Participants completed five runs of go/no-go tasks during functional MRI (fMRI). There were three task conditions: 1) interests (non-social), 2) facial expressions (social) and 3) colored shapes (control). As depicted in Figure 1, within a single run, a specific category of cues served as a go (i.e. target) stimulus to which participants were instructed to press a button and another category of cues served as a nogo (i.e. nontarget) stimulus for which participants withheld a button press. For the interest conditions, 12 unique images of each participant’s favorite activity (interest) and 12 unique images of the participant’s least favorite activity (non-interest) were presented randomly as the target or nontarget and were reversed in a second run. In the social condition, similar to previous work (Hare and Casey, 2005), 12 (6M, 6F) happy and 12 (6M, 6F) calm faces from the NimStim set (Tottenham et al., 2009) were presented as the target and nontarget stimuli and reversed as the target and nontarget in a second run. Finally, in the control condition, a single run of blue and yellow rectangles (colors) served as target and nontarget stimuli. The five runs were counterbalanced across subjects. Participants practiced the task outside of the scanner with colored shapes so that they understood the instructions.

Each run was 5 min and 58 s and contained 77 go-stimuli and 30 nogo-stimuli, presented in a pseudorandomized order. Within each trial, the go and nogo stimuli were presented for 750 ms followed by a jittered intertrial interval (2–14 s) (described in detail in the Supplementary Material). A five-button MR-compatible button box was used to record button responses and reaction times. The experimental task was presented using E-Prime 2.0 and was projected onto a flat screen mounted in the scanner bore.

fMRI data acquisition

Whole-brain fMRI data were acquired using a Siemens Magnetom Prisma 3T scanner located at the Citigroup Biomedical Imaging Center (CBIC) at Weill Cornell Medicine. A high-resolution, T1-weighted magnetization-prepared rapid-acquisition gradient-echo sequence scan was acquired (TR/TE = 2400/2.12 ms, Field of View (FOV) = 256 mm, 1.0 mm isotropic). Two fieldmap images were acquired in opposing phase-encoding directions (TR/TE = 8860/80 ms, FOV = 216 mm, multiband factor = 6, echo spacing = 0.56 ms, 2.4 mm isotropic). Functional images were acquired using T2*-sensitive echoplanar pulse sequences covering the full brain. Sixty-six axial slices were acquired per 800 ms TR (TE = 30 ms, FOV = 216 mm, flip angle = 49°, multiband factor = 6, echo spacing = 0.56 ms, 2.4 mm isotropic)(Feinberg et al., 2010; Moeller et al., 2010; Setsompop et al., 2012; Xu et al., 2012).

Behavioral data analysis

Behavioral data and stimulus timing information were extracted and calculated using MATLAB and Statistics Toolbox Release 2016b (MathWorks, Natick, USA). Analyses were conducted separately for the non-social and social conditions due to qualitative difference in how participants interacted with the stimuli prior to the experiment, i.e. participants were given a choice of stimuli in the non-social conditions, which was not the case in the social conditions. The color condition was added to both analysis designs to serve as a neutral control comparison. Participants were included in behavioral and imaging analyses if accuracy on go-trials was >70% and false alarms during nogo-trials was <50% (described in detail in the Supplementary Material). Three participants were excluded from analyses in the colors condition, six in the non-social condition and four in the social condition.
Mean reaction time (RT) to correct go-trials was computed for each condition. Trials with RT’s faster than 200 ms were considered invalid responses and consequently excluded. In addition to mean RT, to better capture the characteristics of RTs across conditions, ex-Gaussian parameters were computed (\( \mu \), \( \sigma \), and \( \tau \)) by fitting the ex-Gaussian distribution with maximum likelihood estimation to the valid RT’s for correct go-trials (Zandbelt, 2014). \( \mu \) is the mean and \( \sigma \) is the standard deviation from a normal (Gaussian) distribution, and \( \tau \) is the mean and standard deviation of the exponential distribution, thus \( \tau \) typically reflects positive skew in the RT distribution.

As an index of impulsive behavior, the number of false alarms to nogo-trials was calculated, including \( \delta \) by subtracting normalized false alarm rate from normalized accuracy at go-trials (Macmillan and Creelman, 2004).

All statistical analyses were conducted using R (release 3.2.1). We tested for main effects of stimulus type in two analyses, non-social (including colors) and social (including colors) with the dependent variables mean RT, ex-Gaussian parameters \( \mu \), \( \sigma \), and \( \tau \) and false alarms using Linear Mixed-Effects (LME) models (\texttt{lmer} in R: Bates et al., 2014), with task condition as a repeated measures factor, and age as a covariate. Our age range of 18–29 years spans late adolescence into adulthood and prior work suggests age differences to motivational stimuli across this period (Cohen-Gilbert et al., 2014; Cohen et al., 2016). As there were no interactions with age for behavioral or imaging results, age was subsequently no longer included as a covariate in analyses models.

In the presence of a significant main effect, post-hoc pairwise comparisons of the least-squares means were performed (\( F \)-values Tukey-adjusted). In addition, task performance measures that showed a main effect were further interrogated to determine whether there was an association with ASD traits as measured by the SRS and AQ, and ADHD-like traits as measured by the ASR (correlation \( F \)-values were Bonferroni-adjusted to \( P < .016 \) to account for the three conditions tested in each model).

fMRI analysis

Data were preprocessed using a standard pipeline in Analysis of Functional Neuroimages (AFNI) software (version AFNI_16.0.00: Cox, 1996) and FSL (FMRIB Software Library v5.8) (described in detail in the Supplementary Material). A general linear model (GLM) was created for each participant to estimate signal change in response to interests, non-interests, happy faces, calm faces and colors. Each participant’s GLM included 21 regressors: five task regressors for correct responses to the go-stimuli in each condition, five task regressors for correct inhibitions to the nogo-stimuli in each condition, five additional task regressors for false alarms to the nogo-stimuli in each condition and six motion estimation parameters. Time points with a framewise displacement (Power et al., 2014) greater than 0.5 mm were censored, along with the two successive time points. This resulted in the partial exclusion of one participant in the interests condition, as more than 20% of frames needed to be removed. Otherwise an average of 3% of frames were removed per run across all participants (with a maximum of 20% per run, Supplementary Table S2) (for details on the effects of this motion censoring procedure see the Supplementary Material).

Baseline trends were estimated to capture shifts in signal change. Activation in response to the go and nogo stimuli was modeled with a gamma hemodynamic-response function (HRF). Individual-level regression coefficients for 39 participants were submitted to group LME analyses using 3dMEMA (Chen et al., 2013).

Group-level LME-analyses modeled main effects. First, LME analyses were performed with the non-social stimuli and colors, including a random intercept, versus baseline on correct go-trials and correct nogo-trials, respectively. A second LME approach included interests and colors versus baseline, and non-interests and colors versus baseline, on correct go-trials and correct nogo-trials respectively, in order to further interrogate interest-specific differences in impulse control. For facial expressions, two LME-analyses modeled the main effects of the social stimuli and colors, including random intercept, versus baseline on the respective correct go- and nogo-trials. For the non-social and social conditions, a frequently reported nogo > go contrast was performed, however, as expected based on recent suggestions that such a contrast may not be optimal to observe differences across the two constructs (go, nogo) (Craiau and Boulinguez, 2013) no clusters survived whole-brain correction.

Following recent recommendations, the threshold for individual voxels was set at \( P < .001 \) (Cox et al., 2016; Eklund et al., 2016). Estimates for image smoothness for the simulations were calculated using 3dFWHMx and subsequently fed into 3dClustSim (compile date = 01/01/2016). The cluster-size threshold, computed using 10 000 Monte Carlo simulations was set at 38 voxels (\( P < .05 \) after Family Wise Error correction for multiple comparisons).

Using a 6 mm sphere around the peak activation voxel, regression coefficients for individual participants were extracted from regions in the four LME-model maps that showed significant activation after whole brain correction as outlined above and were associated with emotion regulation, salience detection and cognitive control (regions highlighted in the Results section and Supplementary Tables S4–S7).

Subsequent LME analyses were performed on these ROIs (Supplementary Tables S4–S7) to determine condition main effects for non-social and social stimuli (all including colors). \( F \)-values were Bonferroni-adjusted according to the number of ROIs tested. Significant main effects were then followed up with post-hoc pairwise comparisons (difference in least-square means corrected for multiple comparisons using Tukey’s test) and correlations with task performance and ASD and ADHD-like traits in R.

Results

Task performance for interests

Overall, Go accuracy was high (mean = 95.2, SD = 6.4, Figure 3, Supplementary Table S1), with a main effect (\( F_{(0.9)} = 4.1, P = .022 \), demonstrating lower accuracy for non-interests compared to colors and a trend of lower accuracy for non-interests versus interests (Table 2).

Mean reaction times for go-trials differed across conditions (\( F_{(2.69)} = 69.0, P < .001 \)), as participants were significantly slower to their interests and non-interests compared to colors (Table 2, Figure 2A). A similar pattern was observed for the ex-Gaussian parameter \( \mu \) (\( F_{(2.69)} = 51.2, P < .001 \)), where participants demonstrated significantly slower \( \mu \) to interests and non-interests compared to colors (Table 2, Figure 2A). There were no differences in mean RTs or \( \mu \) for interests versus non-interests. The ex-Gaussian parameter \( \tau \) also showed a main effect (\( F_{(2.69)} = 8.4, P < .001 \), with higher \( \tau \) for non-interests as compared to colors (Table 2, Figure 2A). There was no difference in...
Table 2. Pairwise comparisons of the behavioral measures.

|                      | Go Accuracy |                          | Mean RT |                          | Mu      |
|----------------------|-------------|---------------------------|---------|---------------------------|---------|
|                      | β           | s.e. | P       | 95% CI | β           | s.e. | P       | 95% CI | β           | s.e. | P       | 95% CI |
| **Interests**        |             |      |         |        |             |      |         |        |             |      |         |        |
| Colors—Interests     | 0.22       | 1.28 | 0.980   | -2.78  | 3.22        | -76.5 | 8.19    | <.001  | -95.71      | -57.35 | <.001  | -78.32 | -45.75 |
| Colors—Non-interests | 3.26       | 1.26 | 0.033   | 0.31   | 6.22        | -86.8 | 8.03    | <.001  | -105.62     | -67.97 | <.001  | -74.36 | -42.40 |
| Interests—Non-interests | 3.04   | 1.30 | 0.055   | 0.03   | 6.06        | -10.3 | 8.16    | 0.424  | -29.38      | 8.84   | 3.66   | 6.93   | 8.58   |
| **Facial expressions** |           |      |         |        |             |      |         |        |             |      |         |        |
| Colors—Happy faces   |             |      |         |   |    | -78.9 | 8.61 | <.001  | -99.03 | -58.67    | -57.7 | 7.97   | <.001  | -76.39 | -39.00 |
| Colors—Calm faces    | No main effect | | | | | | | | | | | | |
| Happy—Calm faces     |             |      |         |   |    | -24.8 | 8.63 | .015   | -45.07 | -4.62     | -32.3 | 8.00   | <.001  | -55.00 | -13.59 |

|                      | σ           | s.e. | p       | 95% CI | τ           | s.e. | p       | 95% CI |
|----------------------|-------------|      |         |        |             |      |         |        |
| **Interests**        |             |      |         |        |             |      |         |        |
| Colors—Interests     |             |      |         |        |             |      |         |        |
| Colors—Non-interests | No main effect | | | | | | | | | | | | |
| Interests—Non-interests |           | | | | | | | | | | | | |
| **Facial expressions** |           |      |         |        |             |      |         |        |
| Colors—Happy faces   | -5.29      | 3.50 | 0.288   | -13.45 | 2.87        | -14.11 | 6.70 | 0.118  | -30.51 | 2.29     | -28.15 | 6.90 | <.001  | -44.24 | -12.06 |
| Colors—Calm faces    | 16.87      | 3.49 | <.001   | -25.05 | -8.70       | -14.04 | 7.00 | 0.119  | -30.40 | 2.31     | No main effect |
| Happy—Calm faces     | -11.58     | 3.49 | 0.004   | -19.77 | -3.40       | No main effect |

|                      | β           | s.e. | P       | 95% CI | d’-prime  | β           | s.e. | P       | 95% CI |
|----------------------|-------------|      |         |        |           |             |      |         |        |
| **Interests**        |             |      |         |        |           |             |      |         |        |
| Colors—Interests     |             |      |         |        |           | 0.27        | 0.13 | 0.089  | -0.02  | 0.57     | 0.43  | 0.13 | <.001  | 0.18  | 0.54 |
| Colors—Non-interests | No main effect | | | | | | | | | | | | |
| Interests—Non-interests |           | | | | | 0.27  | 0.13 | 0.087  | -0.02  | 0.57     | 0.35  | 0.13 | <.001  | 0.19  | 0.65 |
| **Facial expressions** |           | | | | | | | | | | | | |
| Colors—Happy faces   | -5.22      | 1.70 | 0.009   | -9.19  | -1.24      | -5.22     | 1.70 | 0.009  | -9.19  | -1.24     | 0.65  | 0.13 | <.001  | 0.35  | 0.94 |
| Colors—Calm faces    | -4.82      | 1.75 | 0.022   | -8.92  | -0.71      | -4.82     | 1.75 | 0.022  | -8.92  | -0.71     | 0.51  | 0.13 | <.001  | 0.21  | 0.80 |
| Happy—Calm faces     | 0.40       | 1.50 | 0.961   | -3.10  | 3.90       | 0.40      | 1.50 | 0.961  | -3.10  | 3.90     | -0.14 | 0.12 | 0.508  | -0.43 | 0.15 |

Notes: Pairwise comparisons are only reported in the presence of a significant main effect of task condition. Statistics of main effects are mentioned in the text. Significant pairwise comparisons are displayed in bold. CI = Confidence interval, RT = Reaction time, s.e. = Standard error.
tau between interests versus non-interests or interests versus colors. There was no main effect for the ex-Gaussian parameter sigma ($P = .195$).

$D'$ varied across conditions ($F_{(2, 56)} = 9.23, P < .001$), driven by higher $d'$ for colors compared to non-interests (Table 2, Figure 3A). There was no difference in $d'$ between interests versus non-interests or interests versus colors (Table 2). There was no main effect with the number of false alarms for interests, non-interests and colors during nogo-trials ($P = .088$).

**Task performance for facial expressions**

Go accuracy (mean = 94.6, SD = 6.8, Figure 3, Supplementary Table S1) was similar for happy faces, calm faces and colors. Mean RT on go-trials varied across conditions ($F_{(2, 65)} = 78.2, P < .001$), showing participants were faster to colors versus happy and calm faces (Table 2, Figure 2B). Participants were also faster to happy faces versus calm faces. A similar pattern was observed for the ex-Gaussian parameter mu ($F_{(2, 68)} = 64.7, P < .001$), where all post-hoc pairwise comparisons reached significance with participants showing increasing speeding in their RTs to calm faces, happy faces and colors respectively (Table 2, Figure 2B). The ex-Gaussian parameter sigma was significant ($F_{(2, 71)} = 12.2, P < .001$), showing higher variability to calm faces as compared to colors and higher variability to happy faces versus colors (Table 2, Figure 2B). There was no difference for the ex-Gaussian parameter $\tau_{cu,a}$ varied across conditions ($F_{(2, 63)} = 14.5, P < .001$), as participants had lower $d'$ for both happy and calm faces compared to colors (Table 2, Figure 3B). A similar pattern was observed for the number of false alarms ($F_{(2, 51)} = 5.3, P = .008$) with more errors for happy and calm faces compared to colors.
compared to colors (Table 2). There were no differences in $d'$ or false alarms between happy and calm faces (Table 2).

Correlations between task performance and traits of ASD or ADHD

There was a significant negative correlation between SRS T-scores and mean reaction times on go-trials for Happy faces ($r = -.42, P = .013$), demonstrating adults with more ASD traits had faster mean RTs to happy faces. Participants with higher SRS T-scores (more ASD-like traits) showed less variability in their reaction times for calm faces (lower ex-Gaussian sigma) ($r = -.41, P = .015$). This correlation also remained significant when controlling for ADHD traits. There were no other significant correlations between SRS- or AQ-scores and task performance for interests or facial expressions during go or nogo-trials.

There was a significant correlation between T-scores on the ASR Attention Problems subscale and tau for the color stimuli ($r = .44, P = .014$) that survived Bonferroni-correction, suggesting that adults with more ADHD-like traits had very slow reaction times to the color stimuli in the tail of the RT distribution (higher tau). There were no other significant correlations between ASR scores and task performance for interests or facial expressions.

fMRI results for interests

Extensive patterns of activation throughout the visual, motor and prefrontal cortices were evident during go-trials to interests, non-interests and colors compared to baseline that included the contralateral precentral and fusiform gyrus as well as the orbitofrontal gyrus and insula and several subcortical regions including the putamen and caudate nucleus (Figure 4A, Supplementary Table S4). Successful inhibition (nogo-trials) to interests, non-interests and colors versus baseline demonstrated activation in inhibitory control regions including the bilateral IFG (Figure 4A, Supplementary Table S5). There were no condition effects in the regions that survived whole-brain correction.

A targeted approach interrogating interests and colors only compared to baseline (Figure 4B) showed significantly higher
activation in the left anterior insula (F(1, 32) = 8.0, P = .008) during go-trials for interests compared to colors (Figure 4C). Remaining regions that were interrogated (left and right caudate nucleus, left and right putamen and left IFG) did not demonstrate condition effects during go-trials. A second model with non-interests and colors only compared to baseline demonstrated stronger deactivation in the right medial frontal gyrus (MFG) (F(1, 34) = 10.0, P = .003) during go-trials for non-interests compared to colors. No other regions (left caudate nucleus) demonstrated condition effects that survived correction. There were no condition effects that survived correction during nogo-trials.

fMRI results for facial expressions

There was activation in emotion regulation circuitry, including bilateral amygdala, dorsolateral prefrontal cortex (DLPFC) and ventromedial PFC (vmPFC) during go-trials to emotional faces and colors versus baseline (Figure 5A, Supplementary Table S6). There was a difference across conditions in the right DLPFC (F(2, 66) = 5.2, P = .008) (Figure 5B), with increased activation for calm faces as compared to colors (M_{diff} = 0.18, SE = 0.06, P = .006). There was no significant difference in DLPFC activation between happy faces and calm faces (P = .351) or colors (P = .177).

During successful inhibition to emotional faces and colors there was activation in both emotion regulation areas (e.g. amygdala, DLPFC and vmPFC), and inhibitory control areas (e.g. bilateral IFG) (Figure 5A, Supplementary Table S7). In the left DLPFC, close to left IFG (F(2, 70) = 7.3, P = .001), there was increased activation for calm faces as compared to colors (M_{diff} = 0.21, SE = 0.06, P = .001) and calm faces versus happy faces (M_{diff} = 0.15, SE = 0.06, P = .021) during successful nogo-trials.

Brain–behavior relationships for interests and facial expressions

Increased activity in the right DLPFC activation was correlated with increased accuracy during go-trials for emotional faces (r = .35, P = .005). No such correlation was observed with colors. No other correlations between ROIs identified in either the non-social or social conditions of the task, with any other task performance measure or ASD/ADHD traits were significant.

Discussion

The goal of the present study was to develop a neuroimaging paradigm that directly tested whether approach behavior and cognitive control were modulated by stimuli of the subjects’ interest as compared to stimuli of non-interest. In healthy adults, we observed a trend in higher hit rates between interests versus non-interests. Further, interest-specific stimuli were associated with greater activation of the anterior insula. However, adults were quite effective at regulating their impulses towards interest cues, as there were no differences in...
Consistent with our hypotheses, there was a behavioral trend that adults were more accurate to respond to their preferred interest versus non-interest. Our findings were similar to studies that used monetary incentives (Geier and Luna, 2012; Paulsen et al., 2015), speculatively suggesting that one’s interests, like other types of rewarding stimuli, may improve accuracy. Participants’ accuracy was at ceiling on the task, on average 95%, thus it is likely the subtle difference observed between interests and non-interests (P = 0.055) was due to little variability in overall response accuracy. There were no differences between interests versus non-interests in mean or μx RT, however, participants were slower to respond to both interests and non-interests relative to colors, suggesting that the colors were easier stimuli to process compared to the visually more complex images of interests and non-interests. There was no difference in accuracy to interests versus colors, which also highlights a potential attentional bias towards these visually complex, yet preferred stimuli.

There was increased activation to interests as compared to colors in left anterior insula which has consistently been associated with the processing of positive versus negative emotional experiences (Kurth et al., 2010; Duerden et al., 2013) and differentiating emotions (Gorno-Tempini et al., 2001). Increased activity in the anterior insula has also been demonstrated during general arousal (Lewis et al., 2007; Citron et al., 2014), supporting the notion that interests may be differentially motivating for participants. Changes in insular functioning have been consistently reported in many psychiatric disorders that have difficulties with regulation and affective processing such as addiction (Droutman et al., 2015), eating disorders (Schenle et al., 2009; Kim et al., 2012; Oberndorfer et al., 2013), ASD (Uddin et al., 2013; Cascio et al., 2014; Odiviola et al., 2015), depression (Hammer et al., 2013; Iwabuchi et al., 2014), or schizophrenia (Baas et al., 2008; Moran et al., 2013). Thus, the heightened activation observed for interests supports a role for the left anterior insula in an attentional bias to positive, motivating cues. Future work may explore how this pattern of activation is modulated by the intensity of one’s interest.

Contrary to our hypotheses, individuals did not differ in their inhibition to cues depicting preferred hobbies relative to non-interests. However, similar to what was observed in the social condition, the non-social stimuli induced greater impulsivity relative to the control condition of colors. Further, similar to a large literature using go/nogo tasks with a variety of stimuli (Chikazoe et al., 2007; Hare et al., 2008; Wessa and Linke, 2009), frontostriatal control regions including the IFG and the caudate and putamen were engaged during successful inhibition, yet equally so to interests and non-interests. This suggests that although these interest-related stimuli elicit a subtle behavioral attentional bias, it is unlikely that in healthy adults they influence inhibition or decision making in the same way facial expressions or money do (Daw and Doya, 2006; Jones et al., 2011). However, as we highlight in the limitations section below, the interest-specific stimuli were not fully personalized which may have attenuated the behavioral response to these stimuli.

The facial expressions elicited behavioral and neural activation patterns that were consistent with an extensive literature using variations of this task (Hare and Casey, 2005; Shafritz et al., 2006; Schulz et al., 2009). Participants were slower to respond to calm faces relative to happy faces, as reported previously (Hare and Casey, 2005; Schulz et al., 2007; Somerville et al., 2011), suggesting adults demonstrated a greater bias towards happy faces. Notably, faster responses to happy faces were associated with a higher level of ASD-like traits. Further research should determine whether this effect is specific for happy faces, as there is some evidence that individuals with ASD respond faster to emotional faces generally (Yerxa et al., 2013). A frontolimbic circuit including the amygdala and DLPFC was engaged during processing of facial expressions, similar to previous work demonstrating these regions are part of a critical circuit for explicit emotion regulation and appraisal (Phillips et al., 2008; Etkin et al., 2015). The DLPFC demonstrated heightened activation for calm and happy faces relative to colors, which was also related to increased accuracy to faces, supporting a role for this region in top down control in response to emotional stimuli. Although inhibition to the facial expressions differed significantly from colors, we did not find behavioral or neurobiological differences in impulsivity to happy versus calm faces.

Ultimately, the interest-specific go/nogo paradigm may be applied to study clinical populations that have aberrant responses to social and/or non-social stimuli. For instance, children with ASD showed increased activation in left anterior insula (Cascio et al., 2014) and fusiform face area (FFA) (Foss-Feig et al., 2016) when viewing images related to one’s interest, illustrating the increased arousal and visual expertise for these stimuli in ASD. Also, the slight attentional bias found in this healthy adult sample may become more pronounced in clinical populations that have impairments in reward sensitivity, such as in ASD, ADHD or depression. We found no differences based on ASD-like traits in behavioral performance or neural activation to interests versus non-interests, yet it should be noted the majority of these healthy adults had scores within the typical range (<60 on the SRS and <26 on the AQ). Similarly, ASR scores relating to ADHD-like traits were in the typical range (<70 on the ADHD Subscale). In healthy adults, the ex-Gaussian parameter τ was highest for non-interests. The slow and infrequent responses captured by τ have been associated with higher intra-individual variability or attentional lapses, e.g. as seen in ADHD (Geurts et al., 2008; Lin et al., 2015). We found higher scores on the ASR attention problems correlated with higher τ for colors, but there were no differences in τ for interests, non-interests or facial expressions. Overall the findings with τ suggest that the ex-Gaussian parameters uncovered nuances in the behavioral responses to interests and non-interests as compared to neutral or social cues that may be informative for future work in clinical populations (Karalunas et al., 2014).

Limitations

While there is a theoretical basis to directly compare the non-social cues (interests and non-interests) and social cues (facial expressions), such a contrast is problematic due to the nature of how participants engage with these stimuli prior to the task. Participant choice makes the interests and non-interests more personalized, thus future work that asks participants to also choose the social stimuli for the task would address these concerns. A second limitation is that an individual’s hobby may not have been included in the options presented. Nevertheless, all participants expressed that they enjoyed and/or liked their selected hobby, suggesting that their choices were motivating and pleasurable for them. In the absence of independent ratings on the stimuli, future work is needed to assess the validity of the images presented. Despite these limitations, our results suggest this task provides new, valuable information about the
processing of motivating stimuli and can be applied to study psychiatric populations.

Conclusions
We developed a paradigm to test impulse control in response to personalized preferred and non-preferred stimuli. Although no differences were observed in response inhibition, we observed a subtle attentional bias and increased activity in the anterior insula to one’s interests. In our daily activities, at home, school or work, we are constantly exposed to a variety of personally motivating cues, but we are able to choose not to act at every impulse. Together the present findings help to understand how we exert self-control over the temptations in our environment in order to efficiently and successfully navigate the demands of our daily life.

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Supplementary data
Supplementary data are available at SCAN online.

Conflict of interest. None declared.

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