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Dorsal striatum mediates cognitive control, not cognitive effort *per se*, in decision-making: An event-related fMRI study

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ABSTRACT

Objective: Whether the dorsal striatum (DS) mediates cognitive control or cognitive effort *per se* in decision-making is unclear given that these effects are highly correlated. As the cognitive control requirements of a neuropsychological task intensify, cognitive effort increases proportionately. We implemented a task that disentangled cognitive control and cognitive effort to specify the particular function DS mediates in decision-making.
Methods: Sixteen healthy young adults completed a number Stroop task with simultaneous blood-oxygenation-level-dependent response (BOLD) measurement using functional magnetic resonance imaging. Participants selected the physically larger number of a pair of single-digit integers. Discriminating smaller versus larger physical size differences between a number pair requires greater cognitive effort, but does not require greater cognitive control. We also investigated the effect of conflict between the physical and numerical dimensions of targets (e.g., **2** 6). Selections in this incongruent case are more cognitively effortful and require greater cognitive control to suppress responding to the irrelevant dimension. Enhancing cognitive effort or cognitive control demands increases errors and response times. Despite similar behavioural profiles, our aim was to determine whether DS mediates cognitive control or simply indexes cognitive effort, using the same data set.
Results: As expected, behavioural interference effects occurred for both enhanced cognitive control and/or cognitive effort conditions. Despite similar degrees of behavioural interference, DS BOLD signal only correlated with interference arising due to increased cognitive control demands in the incongruent case. DS was not preferentially activated for discriminations of smaller relative to larger physical size differences between number pairs, even when using liberal statistical criteria. However, our incongruent and physical size effects conjointly activated regions related to effortful processing (e.g., anterior cingulate cortex).
Interpretation: We interpret these findings as support for the increasingly accepted notion that DS mediates cognitive control specifically and does not simply index cognitive effort *per se*.

Introduction

Cognitive control processes are required to consider multiple ideas simultaneously, to direct attention from one stimulus dimension to another, and to shift response strategies in accordance with changes in the environment – often requiring inhibition of more automatic or habitual response tendencies (Botvinick et al., 2001; Cools and D'Esposito, 2011; Liu et al., 2004; MacDonald et al., 2000). Deficits in cognitive control result in impaired decision-making in a number of neurological and psychiatric diseases (Beatty and Monson, 1996; Chamberlain et al., 2006; Cools et al., 2001; Ruocco, 2005; Vélez-van-Meerbeke et al., 2013; Verte et al., 2005). Identifying the brain regions that mediate cognitive control will elucidate cognitive-behavioural profiles in disease states, potentially suggesting treatment targets and options.

Controlling attention and flexibly selecting between options was previously thought to be uniquely the domain of the prefrontal cortex (Butters and Rosvold, 1968; Divac, 1972; Goldman and Rosvold, 1972; Rosvold, 1972), but such higher-order processes have recently been ascribed to the dorsal striatum (DS) as well (Cools and D'Esposito, 2011; Crofts et al., 2001; Hazy et al., 2006; MacDonald and Monchi, 2011). DS is defined as the bulk of the caudate and putamen, which are input regions for a collection of subcortical nuclei known as the basal ganglia (Humphries and Prescott, 2010; Voorn et al., 2004; Wickens et al., 2007). DS lesions in both humans and non-human primates result in deficits in shifting attention between stimuli, especially away from more salient ones (Benke et al., 2003; Cools et al., 2003,

Abbreviations: ACC, anterior cingulate cortex; BOLD, blood-oxygenation-level-dependent; DS, dorsal striatum; FDR, false discovery rate; fMRI, functional magnetic resonance imaging; MNI, Montreal Neurological Institute; PD, Parkinson's disease; RT, response time.

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2010; Thoma et al., 2008), in flexibly altering decision-making strategies or response sets (Benke et al., 2003; Cameron et al., 2010; Ell et al., 2006; Grahn et al., 2008; Leber et al., 2008; Yehene et al., 2008), in suppressing more automatic responses (Benke et al., 2003; Cameron et al., 2010; MacDonald et al., 2011; White, 2009), and in updating goals (Grahn et al., 2008; Hazy et al., 2006; Vakil et al., 2004). Parkinson's disease (PD) produces progressive loss of neurons in the substantia nigra—the source of dopamine to DS. Impairments for PD patients in switching attention away from a stimulus (Cools et al., 2003, 2010; Hayes et al., 1998; Shook et al., 2005) or response (Shook et al., 2005; Hood et al., 2007) to another, as well as in selecting between alternatives when there is conflict (MacDonald et al., 2011) also support the notion that DS mediates decisions or selections that require deliberation in the face of competing options or changing circumstances. Concurring with this view, these deficits in PD are redressed by dopamine replacement (Shook et al., 2005; Hood et al., 2007; MacDonald et al., 2011). Finally, many neuroimaging experiments have also shown preferential activity in DS at the time of flexible decision-making and response selection during conflict (Grinband et al., 2006; Monchi et al., 2001; Monchi et al., 2006; Rogers et al., 2000; van Schouwenburg et al., 2010; Ali et al., 2010).

A generally unacknowledged problem with the conclusions about DS drawn from these investigations is that as cognitive control demands of a task are increased, the cognitive effort required correspondingly increases. Cognitive effort has been defined as the proportion of limited-capacity central processing engaged (Russo and Dosher, 1983), the number of elementary processes enacted (Bettman et al., 1990), or the duration over which cognitive resources are expended (Christensen-Szalanski, 1980). Cognitive effort is experimentally dissociable from cognitive control processes. Tests of elaborative rehearsal, vigilance for targets in single visual or auditory streams (Brand and Jolles, 1987), or item comparisons along a single dimension or feature that vary in similarity and, therefore, discriminatory difficulty (Moyer and Landauer, 1967), manipulate cognitive effort independent of cognitive control. The vast majority of studies confound cognitive effort and cognitive control without recognizing or noting this fact. Despite this, the contention that DS engagement could simply index cognitive effort (Boehler et al., 2011; Krebs et al., 2012; Schmidt et al., 2012) remains a minority position in the literature that has not been critically tested. Addressing this confound and more precisely defining the role of DS in cognition was the aim of the current study.

We used a number Stroop task that allowed for independent manipulation of cognitive control and cognitive effort demands. Briefly, in the version of the number Stroop task used here, a pair of single-digit integers was displayed, and participants were asked to select the number in the pair that was physically larger. The numbers could differ in both physical size (i.e., the relevant dimension on which participants based their responses) and numerical value, (i.e., the irrelevant dimension that was always extraneous to enacting the correct response). When the relevant and irrelevant dimensions were incongruent, this provided the means for investigating cognitive control processes. For example, if the physically larger number in a pair is also numerically smaller (e.g., **2** 6), a conflict exists between the relevant and irrelevant dimensions with respect to the concept of magnitude. In this example, the participant must resolve this conflict by directing attention to the relevant dimension, where '2' is the *physically larger* number in the pair, while ignoring the irrelevant dimension in which '2' is the *numerically smaller* number. Trials with number pairs that differ in physical size, but not numerical magnitude, constituted our control condition (e.g., **2** 2). The congruent case arose when the relevant and irrelevant dimensions agreed (e.g., 2 **6**). Responding is often faster and less error-prone during congruent trials compared to incongruent or control trials (Macleod, 1991). Response interference was calculated as the response times (RTs) and error rates in the incongruent condition minus those in the control and congruent conditions. Further, DS activity—assessed using functional magnetic resonance imaging (fMRI) for incongruent compared to control or congruent trials—was contrasted to determine whether DS activity is increased in the incongruent case—where cognitive control as well as cognitive effort demands are greatest (MacLeod, 1991).

Varying the magnitude of the physical size difference between number pairs on the relevant dimension creates the condition for investigating the potential role of DS in cognitive effort. It has been shown previously that longer RTs and higher error rates result when selecting between integers that are closer versus more distant in physical size (Cohen Kadosh et al., 2005; Kaufmann et al., 2005). Similarly, RTs and error rates are increased for discriminations of numerical magnitude when number pairs are numerically closer (e.g., 1 2) relative to more distant (e.g., 1 8) along the number continuum (Moyer and Landauer, 1967). Decreasing the physical size differences of number pairs increases the similarity and, therefore, the difficulty or cognitive effort required to discern which is larger. Smaller versus larger differences between pairs in this comparison task do not differ systematically in the need to shift attention away from salient but irrelevant stimuli or to suppress more automatic or habitual responses (i.e., cognitive control; Botvinick et al., 2001; Cools and D'Esposito, 2011; Liu et al., 2004; MacDonald et al., 2000).

From a behavioural perspective, we expected longer RTs during trials with high cognitive control demands (i.e., the incongruent condition) as well as during trials with high cognitive effort demands (i.e., number pairs with smaller physical size differences). However, if DS mediates cognitive control specifically, DS blood-oxygenation-level-dependent (BOLD) signal should be greater during incongruent relative to control and/or congruent trials (i.e., Stroop interference), but not for trials with smaller relative to larger physical size differences between number pairs (i.e., interference due to physical size difference). Additionally, a negative correlation between DS BOLD signal and Stroop interference scores would indicate a role for DS in cognitive control. Alternatively, if DS merely indexes the cognitive effort required to make decisions, increased DS BOLD signal should correlate positively with RTs during trials that take longer to resolve (i.e., Stroop interference as well as interference due to physical size difference). In this way, we have devised a means for dissociating the role of DS in cognitive control and cognitive effort within the same task, using the same data.

Materials and methods

Participants

Sixteen healthy individuals (8 males, 8 females; mean age 23 years; range 19–27) participated in this experiment. Participants were all healthy, right-handed, and each provided written, informed consent according to the Declaration of Helsinki (1991). All participants had completed at least 12 years of education (range 14–21 years). A small monetary compensation was provided to each participant. This project was approved by the Health Sciences Research Ethics Board of the University of Western Ontario.

Stimuli and design

In this study, participants completed a number Stroop task with simultaneous measurement of regional BOLD activity using fMRI. During each trial, two numbers, from among the set: 1, 2, 3, 7, 8, or 9, appeared side-by-side, each in Arial font size 40, 55, 70, or 85. Participants were asked to select—as quickly yet accurately as possible—the number that was physically larger in the pair.

A single block of 132 randomly ordered trials that included 48 congruent, 48 incongruent, and 36 control trials was performed by each participant (Fig. 1). In the incongruent condition, physical size and numerical magnitude were inconsistent (e.g., 9 **1**). In the congruent condition, physical size and numerical value were consistent (e.g., **9** 1). In the control condition, the numbers in the pair differed only in physical size (e.g., **9** 9).

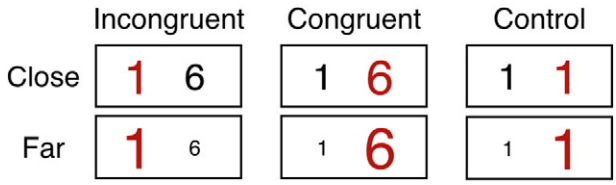

Fig. 1. Number Stroop trial types used in this experiment. Participants were asked to select the physically larger number of the pair. Trials were either: incongruent, in which physically larger numbers are numerically smaller; congruent, where physically larger numbers are numerically larger; or control, in which numbers differ in physical size, but not numerical magnitude. Trial congruency was used to manipulate cognitive control requirements. Physical size differences between number pairs were used to manipulate cognitive effort requirements. Correct responses are shown here in red, but all numbers were black during the experiment.

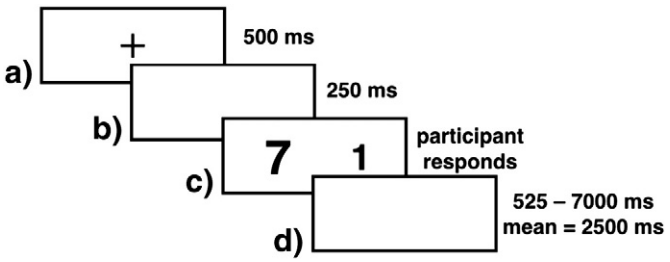

Fig. 2. The progression of a number Stroop trial. a) Trials began with a 500 ms fixation period during which a cross was displayed in the middle of the screen to draw the participant's attention. b) A 250 ms blank screen was then shown. c) The display period began, lasting until the participant logged his/her response via button press. d) An inter-trial interval of variable duration (525–7000 ms; mean = 2500 ms) occurred.

Physical size and numerical magnitude differences between pairs also varied systematically, with possible differences of 15, 30, or 45 font points on the relevant physical size dimension and of 1, 2, 6, or 7 on the to-be-ignored, irrelevant numerical magnitude dimension. Physical size was the relevant dimension because participants were instructed to select the physically larger number of the pair. Numerical magnitude was the irrelevant/distracting dimension because decisions were never based on this information. With respect to the relevant dimension, trials were classified as "close" if the font size difference was 15 points (e.g., font size 40 vs. font size 55) or "far" if the font size difference was 45 points (e.g., font size 40 vs. font size 85). To balance our design and add greater variability to physical size differences between number pairs, trials with an additional, intermediate physical size difference of 30 font points were included in the experiment, but were not considered in our analyses. For numerical magnitude, differences of 1 or 2 between the number pair were classified as "close", whereas differences of 6 or 7 were classified as "far". The physical and numerical difference variables were orthogonal and fully crossed with the congruency variable, allowing for dissociation of their effects. There were 44 trials with a font size difference of 15 points (i.e., close trials), 44 trials with a font size difference of 30 points, and 44 trials with a font size difference of 45 points (i.e., far trials). Additionally, there were 66 trials in which the difference between number pairs on the irrelevant, numerical magnitude dimension was 1 or 2 (i.e., numerically "close") and 66 trials that the difference between number pairs on the irrelevant numerical magnitude dimension was 6 or 7 (i.e., numerically "far"). The close-far variable on the relevant and irrelevant dimensions was fully balanced, such that there were an equal number of close relevant-close irrelevant, close relevant-far irrelevant, far relevant-close irrelevant, and far relevant-far irrelevant pairings.

Procedure

Trials were presented on a projection screen inside an MRI machine. The progression of a number Stroop trial is shown in Fig. 2. Trials began with a 500 millisecond (ms) fixation period, during which a small cross appeared in the center of the screen to capture the attention of the participant. A 250 ms blank screen followed this fixation period. Afterward, a number pair was displayed on the screen – one number on the left and one number on the right. This display period lasted until the participant logged their response with their right hand using a button box. Pressing the button under their right index finger signified a selection of the number on the left side of the screen and the button under their middle finger signified a selection of the number on the right side of the screen. Once a selection was made, an inter-trial interval of variable length (525–7000 ms; mean = 2500 ms) occurred before the presentation of the subsequent fixation period.

Behavioural analyses

All analyses were completed using Systat version 13.1 (Systat Software, San Jose, California). RTs were defined as the period from onset of a number pair until the participant made a response using the button box. Two 3 × 2 analyses of variance (ANOVAs) were performed with congruency (incongruent vs. congruent vs. control) and physical size differences (close vs. far) as within-subject variables to examine the effect of these variables on RTs in one ANOVA, and error rates in the other. Post-hoc tests were performed to understand any main effects. Using two 2 × 2 ANOVAs, with congruency (incongruent vs. congruent) and numerical magnitude differences (close vs. far) as within-subject variables, we further investigated whether the numerical magnitude difference between number pairs on the irrelevant dimension affected participant RTs, error rates, or interacted with the congruency effect. The alpha level was set at 0.05 for all comparisons.

Imaging acquisition

Functional MRI data were collected in a 3 Tesla Siemens Magnetom Trio with Total Imaging Matrix MRI at Robarts Research Institute at the University of Western Ontario. A scout image was obtained for positioning the participant and T1 for anatomical location. There were two runs of T2*-weighted functional acquisitions. The run consisted of one block of 132 trials. All runs lasted an average of 12 minutes with one whole brain image consisting of 43, 2.5-mm-thick slices taken every 2.5 s. The field of view was oriented along the anterior and posterior commissure with a matrix of 88 × 88 pixels, and an isotropic voxel size of 2.5 × 2.5 × 2.5 mm^3. The echo time was 30 ms, and the flip angle was 90°.

fMRI data analyses

Statistical Parametric Mapping version 5 (SPM5; Wellcome Department of Imaging Neuroscience, London, United Kingdom) and Matrix Laboratory (MATLAB; MathWorks, Inc., Natick, Massachusetts, United States) were used to complete fMRI analysis. Images were slice-time corrected, reoriented for participant motion, spatially normalized to the standard Montreal Neurological Institute (MNI) template, and smoothed with an 8 mm full-width, half-maximum Gaussian kernel. Brain regions mentioned in this paper were defined using the Harvard-Oxford Subcortical and Cortical Atlases in the FMRIB Software Library version 5.0 (FSL v5.0; Analysis Group, FMRIB, Oxford, United Kingdom). All *x*, *y*, *z* values are reported in MNI space.

Each participant's data were modeled using fixed effects analyses in SPM5. Predictor functions were formed by convolving onsets and durations of psychological events of interest with the canonical hemodynamic response function. Trials were organized by both congruency (i.e., congruent, incongruent, or control) and physical size differences

(i.e., close or far) between the number pairs displayed during trials. Again, these effects were orthogonal and fully crossed so each variable could be investigated by collapsing across the other variable. A 3 × 2 fully factorial ANOVA, with congruency (congruent vs. incongruent vs. control) and physical size difference (close vs. far) as within-subject variables was performed on BOLD signal. To match our behavioural analyses, pairwise effects were investigated to better understand any main effects.

In addition, to determine whether DS is differentially implicated in cognitive control processes or engaged generally in conditions with high cognitive effort demands, conjunction analyses between Stroop interference and close-far physical distance contrasts were performed at the whole-brain level. Disjunction analyses were also completed to demonstrate that DS is significantly more active in our incongruent – congruent contrast than our close – far contrast. We followed these analyses with region of interest (ROI) analyses conducted using peak MNI coordinates in DS (±16, −10, 18) taken from a Stroop interference study by Peterson et al. (1999). In addition to the DS ROIs intended to distinguish engagement in cognitive control versus cognitively effortful processing, we selected an ROI in the anterior cingulate cortex (ACC; ±11, 1, 50; Ansari et al., 2006). An ACC ROI was used because this brain region is frequently preferentially engaged in tasks that demand significant attention or sustained cognitive effort (Shenhav et al., 2013; Ansari et al., 2006; Kaufmann et al., 2005; MacDonald et al., 2014). Therefore, we supposed that this region might be commonly activated for interference and physical size comparison contrasts. ROIs used in our analyses were 5 mm spheres drawn around the coordinates listed in the studies cited above. Finally, brain-behaviour correlations of BOLD signal with our interference scores due to congruency and physical distance were performed.

Results

Behavioural results

Mean RTs and error rates sorted by congruency, physical size differences, and numerical magnitude differences are presented in Table 1. Interference (incongruent – control, incongruent – congruent) and facilitation (congruent – control) effects are shown in Fig. 3. One-sample *t*-tests (theoretical mean = 0) indicate significant response slowing in our interference (incongruent – control, $t_{(15)} = 6.319$, $p < 0.001$; incongruent – congruent, $t_{(15)} = 8.525$, $p < 0.001$) contrasts and faster responding in our facilitation (congruent – control, $t_{(15)} = 2.167$, $p < 0.05$) contrast (Fig. 3). An additional one-sample *t*-test (theoretical mean = 0) indicates significant response slowing (close – far, $t_{(15)} = 4.047$, $p < 0.005$) during trials with close physical size differences compared to trials with far physical size differences (Fig. 4). A one-way ANOVA found no differences in the magnitude of response slowing between our interference (incongruent – control, incongruent – congruent) and close – far contrasts ($F_{(2, 45)} = 0.5157$, $MSE = 1152$, $p = 0.60$). This indicates that an equal amount of cognitive effort was required to respond correctly during incongruent trials and trials with close physical size differences.

Table 1
Mean RTs (ms ± SEM) and error rates (% ± SEM) for trials sorted by congruency, physical size difference, and numerical magnitude difference.

Congruency	Physical size	Numerical magnitude	RT (ms ± SEM)	Error rates (% ± SEM)
Incongruent	–	–	477.75 ± 19.01	7.55 ± 1.45
	Close	–	553.79 ± 22.23	11.33 ± 3.34
	Intermediate	–	464.17 ± 18.12	3.52 ± 0.99
	Far	–	440.56 ± 18.92	3.52 ± 1.61
	–	Close	468.44 ± 16.79	5.73 ± 5.67
	–	Far	484.16 ± 23.91	8.07 ± 8.40
Congruent	–	–	423.24 ± 16.90	4.56 ± 0.39
	Close	–	450.05 ± 21.25	3.52 ± 0.98
	Intermediate	–	424.80 ± 17.98	3.13 ± 0.81
	Far	–	406.17 ± 13.76	3.13 ± 0.81
	–	Close	423.61 ± 15.96	3.39 ± 0.57
	–	Far	424.92 ± 17.53	3.39 ± 0.57
Control	–	–	436.69 ± 18.85	3.65 ± 0.42
	Close	–	477.58 ± 27.68	2.60 ± 1.00
	Intermediate	–	431.31 ± 15.11	2.60 ± 1.00
	Far	–	409.60 ± 15.94	1.56 ± 0.84
–	Close	–	487.64 ± 22.10	7.10 ± 1.19
–	Intermediate	–	440.40 ± 17.70	3.84 ± 0.45
–	Far	–	417.65 ± 15.84	3.69 ± 0.80

Horizontal dashes indicate that trials used to determine RTs and error rates in that row are collapsed across the column variable. With respect to the physical size variable, "Close" denotes a font size difference of 15 points, "Intermediate" denotes a difference of 30 points, and "Far" denotes a difference of 45 points. "Intermediate" physical size trials were not used in our subsequent analyses, but are listed here for the sake of completeness. With respect to the numerical magnitude variable, "Close" denotes numerical magnitude differences of 1 or 2 and "Far" denotes numerical magnitude differences of 6 or 7.

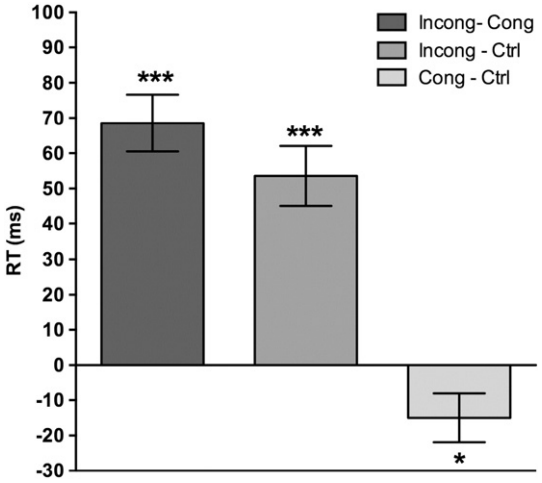

Fig. 3. Stroop interference and facilitation scores. Interference scores are (mean incongruent RT – mean congruent RT, and mean incongruent RT – mean control RT). Facilitation score is (mean congruent RT – mean control RT). Error bars represent ± SEM. Close and far trials of each congruency type (collapsed across numerical magnitude difference) were used. One-sample *t*-tests (theoretical mean = 0) were completed for each bar. Triple asterisks denote significantly different mean RTs at $p < 0.001$. A single asterisk denotes significantly different mean RTs at $p < 0.05$. Cong, congruent; Ctrl, control; Incong, incongruent.

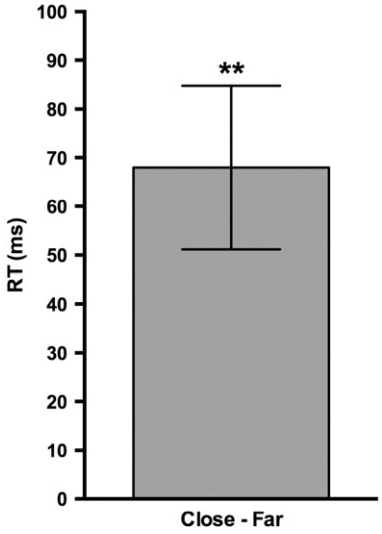

Fig. 4. Response slowing due to physical size differences. Response slowing was determined by subtracting mean RT during far trials from mean RT during close trials. Error bars represent ± SEM. Close and far trials were collapsed across congruency and numerical magnitude difference. A one-sample *t*-test (theoretical mean = 0) indicated significant response slowing at $p < 0.005$.

We ran a 3 × 2 ANOVA on RTs, with congruency (incongruent vs. congruent vs. control) and physical size difference between number pairs (close vs. far) as within-subject variables to determine the effect of these factors on RTs. Significant main effects of congruency ($F_{(2, 90)} = 6.203$, $MSE = 41589$, $p < 0.005$) and of physical size difference ($F_{(1\ 90)} = 20.33$, $MSE = 136310$, $p < 0.001$) were observed. There was no significant interaction between congruency and physical size ($F_{(2, 90)} = 1.442$, $MSE = 9670$, $p = 0.24$). Bonferroni-corrected post-hoc *t*-tests revealed that participants had longer RTs during incongruent trials than during congruent ($t_{(90)} = 3.350$, $p < 0.005$) or control ($t_{(90)} = 2.618$, $p < 0.05$) trials. However, mean RTs during congruent and control trials did not differ significantly ($t_{(90)} = 0.73$, $p > 0.99$).

We performed an analogous 3 × 2 ANOVA on error rates, with congruency (incongruent vs. congruent vs. control) and physical size differences between number pairs (close vs. far) as within-subject variables. Main effects of congruency ($F_{(2, 90)} = 5.496$, $MSE = 249.9$, $p < 0.01$) and physical size difference ($F_{(1, 90)} = 5.013$, $MSE = 227.9$, $p < 0.05$) were observed. No significant interaction between congruency and physical size difference ($F_{(2, 90)} = 2.972$, $MSE = 135.1$, $p = 0.056$) was seen on error rates. Bonferroni-corrected post-hoc *t*-tests revealed that participants made more errors during incongruent trials than during congruent ($t_{(90)} = 2.433$, $p < 0.05$) or control ($t_{(90)} = 3.167$, $p = 0.01$) trials, but error rates for control and congruent trials did not differ ($t_{(90)} = 0.7338$, $p > 0.99$). Further, participants made more errors during close incongruent trials compared to close congruent ($t_{(90)} = 3.277$, $p < 0.005$) or close control ($t_{(90)} = 3.659$, $p < 0.005$) trials, but error rates for close congruent and close control trials did not differ ($t_{(90)} = 0.3823$, $p > 0.99$). There were no differences in error rates for far trials crossing the congruency variable.

We next examined whether the numerical magnitude difference between number pairs (i.e., the irrelevant dimension) affected the size of the interference or facilitation effects using a 2 × 2 ANOVA, with congruency (incongruent vs. congruent) and numerical magnitude difference between number pairs (close vs. far) as within-subject factors. A main effect of congruency ($F_{(1, 60)} = 9.308$, $MSE = 63905$, $p < 0.005$), but not of numerical magnitude ($F_{(1, 60)} = 0.5071$, $MSE = 3482$, $p = 0.48$) was observed. Most important, there was no significant interaction between congruency and numerical magnitude difference ($F_{(1, 60)} = 0.0754$, $MSE = 517.7$, $p = 0.78$), suggesting that the size of interference and facilitation effects was not significantly affected by the numerical magnitude difference between number pairs on the irrelevant dimension.

A similar 2 × 2 ANOVA, with congruency (incongruent vs. congruent) and numerical magnitude difference (i.e., the irrelevant dimension) between number pairs (close vs. far) as within-subject factors was used to investigate the effects of both factors on error rates. A main effect of congruency ($F_{(1, 60)} = 12.86$, $MSE = 549.3$, $p < 0.001$), but not of numerical magnitude difference ($F_{(1, 60)} = 0.0572$, $MSE = 2.441$, $p = 0.81$) was observed. There was no significant interaction between congruency and numerical magnitude difference ($F_{(1, 60)} = 0.2286$, $MSE = 9.766$, $p = 0.63$), suggesting that error rate was not significantly affected by the difference between number pairs on the irrelevant dimension.

Imaging results

We examined BOLD signal in a 3 × 2 fully factorial model, with congruency (incongruent vs. congruent vs. control) and physical size differences (close vs. far) as within-subject variables. As shown in Table 2, right dorsal putamen (*peak coordinates:* 27, -7, 1; $F_{(1, 90)} = 12.35$; *cluster size* = 3) was significant for main effect of congruency at $p < 0.05$ with false discovery rate (FDR) correction. All regions differentially modulated by congruency are listed in Table 2.

To mirror our behavioural analyses, we investigated brain regions that were preferentially activated by interference (incongruent – control, incongruent – congruent) and the reverse contrasts (control – incongruent, congruent – incongruent), as well as contrasts of congruent and control conditions. Table 3 presents brain regions that were significant at $p < 0.05$ with FDR correction for these pairwise comparisons. In the incongruent – congruent contrast, activations in right dorsal caudate (*peak coordinates:* 21, 5, 25; $t = 3.33$; *cluster size* = 54), left dorsal caudate (*peak coordinates:* -18, -4, 19; $t = 2.85$; *cluster size* = 2), and left dorsal putamen (*peak coordinates:* -30, -1, 10; $t = 2.73$; *cluster size* = 2) all survived FDR correction. The significant activations for these contrasts are shown in Fig. 5. In addition, there were right dorsal caudate (*peak coordinates:* 27, -7, 1; $t = 3.51$) and left dorsal caudate (*peak coordinates:* −18, −22, 19; $t = 3.10$) peaks found as secondary activations within large clusters originating in the right postcentral gyrus and left superior temporal gyrus, respectively. Neither dorsal caudate nor putamen were significantly more active in the remaining pairwise comparisons (i.e., incongruent – control; control – incongruent; congruent – incongruent; congruent – control; control – congruent). However, given that striatum was predicted in our incongruent – control contrast, and because a region of DS was significant at $p < 0.05$ with FDR correction in our omnibus test of congruency, we further explored striatum in the incongruent – control contrast using $p < 0.005$ uncorrected for multiple comparisons with a cluster size cutoff of 10 contiguous voxels. BOLD signal in right dorsal putamen (*peak coordinates* 36, −1, 4; $t = 3.42$; *cluster size* = 48), and left dorsal putamen (*peak coordinates* −30, −1, 13; $t = 3.11$; *cluster size* = 13) were significant at this more liberal threshold for the incongruent –

Table 2
Regions significant for main effect of congruency.

Anatomical Region	Coordinates (*x*, *y*, *z*)	*F* value	Cluster size
R dorsal putamen	**27, −7, 1**	**12.35**	**3**
R postcentral gyrus	66, −7, 13	22.62	764
	36, −31, 40	16.55	21
	45, −37, 61	14.76	42
	57, −19, 52	10.84	1
L superior temporal gyrus	−60, −4, −1	21.33	72
L postcentral gyrus	−33, −34, 46	18.96	130
L cerebellum	−18, −58, −17	18.65	31
	−9, −31, −23	15.55	14
R inferior temporal gyrus	60, −58, −11	18.58	57
	48, −22, −23	11.91	1
	45, −25, −20	11.10	1
	48, −55, −20	10.90	1
R hippocampus	21, −25, −11	17.37	70
R frontal orbital cortex	18, 32, −17	17.33	8
R amygdala	18, 2, −20	15.96	36
L planum temporale	−51, −31, 7	14.83	62
L juxtapositional lobule cortex (ext. into anterior cingulate cortex)	−12, 5, 46	14.36	9
L/R occipital pole	0, −91, 22	14.36	15
L insular cortex	−39, 2, −17	13.86	6
	−33, −25, 16	10.99	1
L superior parietal lobule	−18, −49, 55	13.58	6
L posterior cingulate gyrus	−15, −25, 34	13.52	6
R planum temporale	51, −28, 13	13.19	7
R lateral occipital cortex	24, −67, 46	13.03	9
L hippocampus	−21, −19, −11	12.97	4
R frontal operculum cortex	33, 14, 16	12.90	6
	30, 29, 10	11.97	4
R dorsolateral prefrontal cortex	39, 44, 28	12.51	19
R orbitofrontal cortex	30, 38, −17	11.80	2
R insular cortex	39, 5, −17	11.74	2
R posterior cingulate gyrus	15, −31, 37	11.68	8
R thalamus	12, −19, 4	11.33	2
R white matter	21, 5, 25	11.06	1
L precentral gyrus	−57, −4, 25	11.05	2
L temporal fusiform cortex	−42, −28, −17	10.85	1

All *F* values listed above were found at $p < 0.05$ with FDR correction. Coordinates are listed in MNI space. ext, extending; L, left; R, right.

Table 3
Significant activations in pairwise comparisons of incongruent, congruent, and control trials.

Contrast	Anatomical Region	Coordinates (*x*, *y*, *z*)	*t*-stat	Cluster size
incongruent – congruent	**R dorsal caudate**	**21, 5, 25**	**3.33**	**54**
	L dorsal caudate	**−18, −4, 19**	**2.85**	**2**
	L dorsal putamen	**−30, −1, 10**	**2.73**	**2**
	R postcentral gyrus	66, −7, 13	4.76	2368
	(R dorsal putamen)	(**27, −7, 1**)	(**3.51**)	*
	L superior temporal gyrus	−60, −4, 1	4.62	596
	(L dorsal caudate)	(**−18, −22, 19**)	(**3.10**)	*
	L postcentral gyrus	−33, −34, 46	4.35	554
	L cerebellum	−18, −58, −17	4.32	134
	R inferior temporal gyrus	60, −58, −11	4.31	157
		48, −22, −23	3.45	14
	R parahippocampal gyrus	21, −25, −11	4.17	448
	R frontal orbital cortex	18, 32, −17	4.16	42
	L juxtapositional lobule cortex (ext. into anterior cingulate cortex)	−12, 5, 46	3.79	107
	L/R occipital pole	0, −91, 22	3.79	68
	L insular cortex	−39, 2, −17	3.72	18
	L hippocampus	−21, −19, −11	3.60	35
	R dorsolateral prefrontal cortex	39, 44, 28	3.54	126
	R frontal operculum cortex	30, 29, 10	3.46	20
	R thalamus	12, −19, 4	3.37	23
		21, −31, 7	2.78	1
	L temporal fusiform cortex	−42, −28, −17	3.29	14
		39, −13, −23	2.85	3
	R posterior cingulate gyrus	3, −43, 4	3.13	13
		3, −34, 28	2.82	4
	L middle frontal gyrus	−39, 38, 34	3.12	12
	L supramarginal gyrus	−36, −49, 19	3.07	8
	L lateral occipital cortex	−54, −67, −11	3.06	10
	R ventromedial prefrontal cortex	48, 50, 13	3.02	20
	R temporal occipital fusiform cortex	24, −61, −14	3.02	39
	L/R lingual gyrus	0, −70, 7	3.01	14
	R occipital fusiform gyrus	30, −82, −20	3.01	2
	L occipital fusiform gyrus	−36, −76, −23	3.00	10
	L thalamus	−18, −31, 4	2.98	10
	L lingual gyrus	−15, −46, −5	2.96	25
	L inferior temporal gyrus	−45, −52, −5	2.95	3
	L subcallosal cortex	−12, 17, −11	2.79	3
	R intracalcarine cortex	24, −61, 10	2.78	11
	R inferior frontal gyrus	45, 32, 7	2.78	2
	R lingual gyrus	12, −88, −11	2.73	1
	L cerebellum	−24, −40, −29	2.72	1
	R precentral gyrus	21, −25, 58	2.71	1
	R precuneus	3, −49, 61	2.67	2
congruent – incongruent	–	–	–	–
incongruent – control	–	–	–	–
control – incongruent	–	–	–	–
congruent – control	–	–	–	–
control – congruent	L cuneus	−6, −85, 37	5.28	2425
	R supramarginal gyrus	69, −25, 31	4.58	2668
	L superior temporal gyrus	−63, −7, −2	4.56	238
	R frontal orbital cortex	18, 32, −17	4.37	42
	R thalamus	18, −19, 7	3.34	66
	L insular cortex	−30, −25, 16	3.21	38
	L cerebellum	−18, −28, −32	3.18	20
	L frontal orbital cortex	−24, 8, −23	3.14	8
	R orbitofrontal cortex	21, 59, −5	3.10	12
	R dorsolateral prefrontal cortex	27, 47, 40	3.07	15
	R inferior frontal gyrus	33, 32, 10	3.03	3
	L dorsolateral prefrontal cortex	−30, 44, 37	2.93	20
	L temporal fusiform cortex	−30, −31, −23	2.88	7
	R hippocampus	18, −22, −11	2.87	3
	L temporal pole	−51, 14, −20	2.85	2
	L frontal medial cortex	−3, 38, −14	2.85	10
	R middle temporal gyrus	63, −37, −11	2.85	4
	R inferior frontal gyrus	48, 29, 10	2.84	3
	L amygdala	−21, −4, −17	2.82	5
	L postcentral gyrus	−42, −28, 40	2.82	4
	R middle temporal gyrus	63, −52, −11	2.72	2
	R ventrolateral prefrontal cortex	42, 50, 13	2.63	2
	L hippocampus	−27, −7, −23	2.62	1
	R orbitofrontal cortex	30, 38, −17	2.61	1

All *t* values listed above were found at $p < 0.05$ with FDR correction. Secondary DS activations are listed in parentheses below their primary activations. Coordinates are listed in MNI space. ext, extending; L, left; R, right.

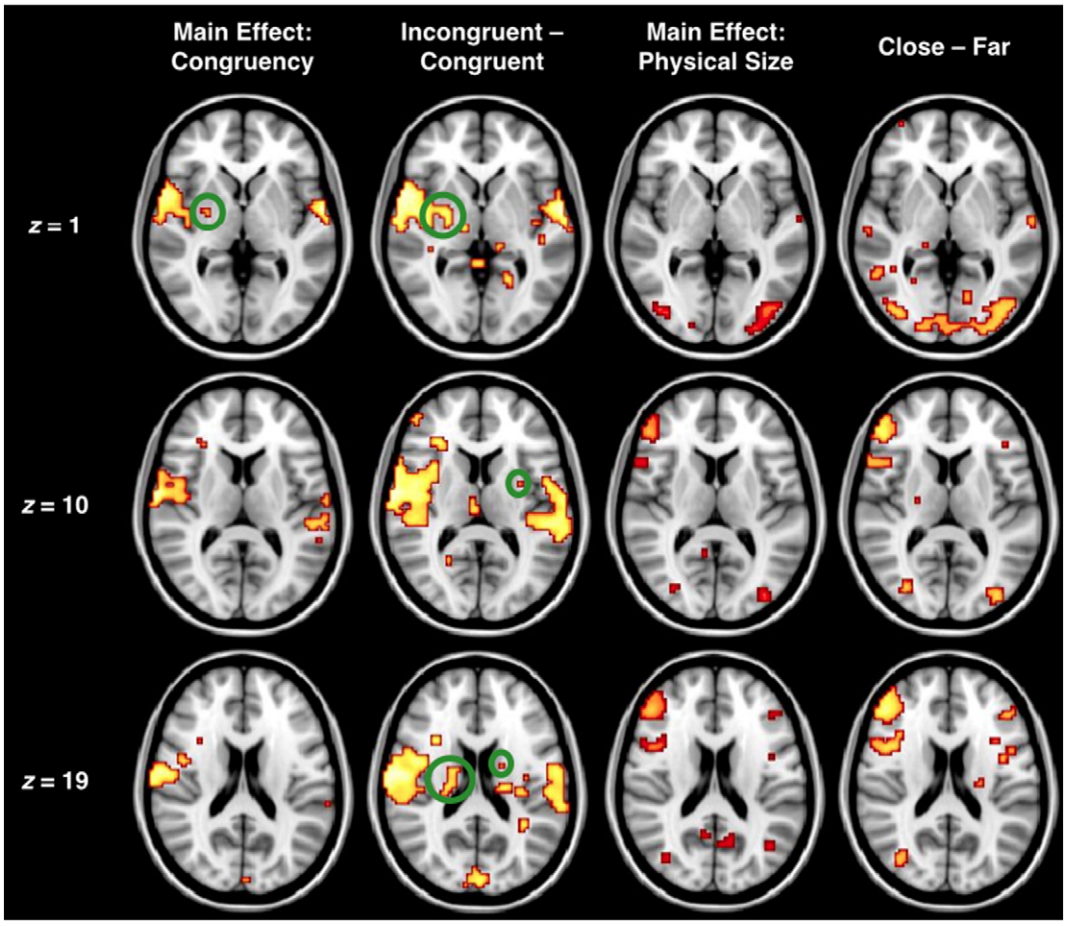

Fig. 5. Axial slices showing significant activations for our BOLD signal analyses. Activations seen in contrasts of interest are shown in vertical columns for $z = 1$, 10, and 19. Significant activations ($p < 0.05$ with FDR correction) in DS are circled in green.

control contrast. No DS activations were seen at this threshold in the control – incongruent contrast.

In our 3 × 2 ANOVA, we found no regions in DS that were significant for main effect of physical size difference at $p < 0.05$ with FDR correction for multiple comparisons. All regions significantly modulated by physical size difference are shown in Table 4. To be entirely sure that DS was not implicated in this effect, we set a very liberal threshold of $p < 0.05$ uncorrected for multiple comparisons, with a cluster size cutoff of 10 contiguous voxels. We again found no significant voxels within DS. We then investigated pairwise contrasts of close – far and far – close at $p < 0.05$ with FDR correction (Table 5). There were no significant activations in DS in either contrast. Using a very liberal threshold of $p < 0.05$ uncorrected for multiple comparisons, with a cluster-size cutoff of 10 contiguous voxels, there were no significant activations in DS. A single non-significant activation in DS was noted in right dorsal putamen (*peak coordinates:* 30, 5, 10; $t = 1.70$; *cluster size* = 4) that disappeared at a threshold of $p < 0.01$ uncorrected for multiple comparisons.

In the same 3 × 2 ANOVA with a statistical threshold of $p < 0.05$ with FDR correction, clusters extending into ACC – originating at the border of the left juxtapositional lobule – were observed in our main effect contrasts for both congruency (*peak coordinates* −12, 5, 46; $F_{(1, 90)} = 14.36$; *cluster size* = 9) and physical size difference (*peak coordinates* −15, 2, 43; $F_{(1, 90)} = 15.22$; *cluster size* = 14). In subsequent pairwise comparisons, both ACC activations were also seen in our incongruent – congruent (*peak coordinates* −12, 5, 46; $t = 3.79$; *cluster size* = 107) and close – far (*peak coordinates* −15, 2, 43; $t = 3.90$; *cluster size* = 66) contrasts. As well, left supramarginal gyrus (*peak coordinates* −36, −49, 19; $t = 3.07$; *cluster size* = 8) was significant in our incongruent – congruent contrast. Right supramarginal gyrus was significant in both the main effect of physical size difference (*peak coordinates* 69, -22, 28; $F_{(1, 90)} = 11.21$; *cluster size* = 4) and pairwise

Table 4
Regions significant for main effect of physical size difference.

Anatomical Region	Coordinates (*x*, *y*, *z*)	*F* value	Cluster size
R middle temporal gyrus	54, −55, 11	36.06	1518
L inferior temporal gyrus	−45, −55, −8	29.68	447
R precentral gyrus	45, 8, 25	29.64	353
L precentral gyrus	−45, 2, 28	29.41	194
R ventrolateral prefrontal cortex	48, 38, 16	22.91	171
L lateral occipital cortex	−45, −76, 34	21.25	89
L superior parietal lobule	−27, −55, 49	17.98	272
L cerebellum	−3, −73, −23	17.70	41
L posterior cingulate gyrus	−6, −37, 43	15.94	26
L juxtapositional lobule cortex (ext. into anterior cingulate cortex)	−15, 2, 43	15.22	14
R frontal medial cortex	3, 32, −17	12.54	108
R orbitofrontal cortex	21, 47, −14	11.60	4
R occipital pole	18, −91, 4	11.57	8
R supramarginal gyrus	69, −22, 28	11.21	4
R inferior frontal gyrus	57, 17, 7	11.03	12
R precuneus	9, −55, 10	10.99	13
L precuneus	−12, −58, 16	10.68	13
L brain stem	−9, −22, −32	10.54	1
L middle frontal gyrus	−45, 35, 19	10.25	5
L inferior frontal gyrus	−30, 32, 16	10.02	4
L paracingulate gyrus	−6, 53, −2	9.93	5
L superior temporal gyrus	−63, −10, 1	9.28	2

All *F* values listed above were found at $p < 0.05$ with FDR correction. Coordinates are listed in MNI space. ext, entending; L, left; R, right.

Table 5
Significant activations for pairwise comparisons of close and far trials.

Contrast	Anatomical Region	Coordinates (*x*, *y*, *z*)	*t*-stat	Cluster size
close – far	R inferior temporal gyrus	54, −55, −11	6.01	1862
	L inferior temporal gyrus	−45, −55, −8	5.45	729
	R precentral gyrus	45, 8, 25	5.44	523
	L precentral gyrus	−45, 2, 28	5.42	264
		−33, −4, 43	2.82	6
	R ventrolateral prefrontal cortex	48, 38, 16	4.79	217
	L superior parietal lobule	−27, −55, 49	4.24	470
	L cerebellum	−3, −73, −23	4.21	81
	L juxtapositional lobule cortex (ext. into ACC)	−15, 2, 43	3.90	66
	R orbitofrontal cortex	21, 47, −14	3.41	15
		36, 53, −14	2.98	3
		36, 62, 1	2.75	1
		36, 44, −17	2.73	1
	R supramarginal gyrus	69, −22, 28	3.35	11
	L brain stem	−9, −22, −32	3.25	2
	L middle frontal gyrus	−45, 35, 19	3.20	37
	L superior temporal gyrus	−63, −10, 1	3.05	11
	L intracalcarine cortex	−21, −76, 7	2.94	19
	L orbitofrontal cortex	−45, 47, −14	2.92	5
	R postcentral gyrus	6, −37, 61	2.88	4
	L temporal occipital fusiform cortex	−39, −49, −26	2.85	2
	R superior temporal gyrus	60, −22, −2	2.85	9
	L temporal fusiform cortex	−36, −4, −29	2.81	1
	R occipital pole	6, −91, 25	2.81	1
	L brain stem	−12, −19, −29	2.81	1
	R planum polare	39, −1, −20	2.79	1
	R lingual gyrus	12, −70, −14	2.77	1
		27, −58, 4	2.76	2
	R white matter	15, 2, 55	2.75	1
		21, 8, 25	2.74	2
		24, −13, 10	2.73	1
	R lateral ventricle	15, 26, 7	2.72	2
	R thalamus	18, −31, 1	2.71	1
	L lateral occipital cortex	−24, −70, 28	2.70	1
		−27, −73, 25	2.68	1
	L middle temporal gyrus	−66, −25, −5	2.67	1
far – close	–	–	–	–

All *t* values listed above were found at $p < 0.05$ with FDR correction. Coordinates are listed in MNI space. ext, extending; L, left; R, right.

Table 6
Conjunction analyses of our interference and close – far contrasts.

Conjunction	Anatomical Region	Coordinates (*x*, *y*, *z*)	*t*-stat	Cluster size
incongruent – congruent ∩ close – far	R inferior temporal gyrus	60, −58, −11	4.31	144
	R postcentral gyrus	36, −31, 37	4.06	406
	L juxtapositional lobule cortex (ext. into anterior cingulate cortex)	−12, 2, 43	3.43	9
	R precentral gyrus	48, 2, 25	3.42	30
	R supramarginal gyrus	69, −22, 28	3.35	15
	L postcentral gyrus	−36, −37, 43	3.21	80
	L supramarginal gyrus	−51, −31, 49	3.11	26
	R inferior frontal gyrus	60, 17, 7	3.07	7
	L lateral occipital cortex	−54, −67, −11	3.06	7
	L superior temporal gyrus	−63, −10, 1	3.05	14
	R ventrolateral prefrontal cortex	48, 50, 13	3.02	14
	R superior parietal lobule	24, −49, 55	3.02	15
	R lateral occipital cortex	36, −76, −23	3.00	10
	R dorsolateral prefrontal cortex	42, 41, 25	2.75	5
incongruent – control ∩ close – far	R inferior temporal gyrus	54, −58, −11	4.00	91
	R supramarginal gyrus	42, −34, 31	3.35	114
	R angular gyrus	45, −49, 58	3.32	55
	R lateral occipital cortex	48, −76, −11	3.22	13
	L superior parietal lobule	−39, −40, 46	3.17	52
	L supramarginal gyrus	−51, −31, 49	2.77	7

All *t* values listed above were found at $p < 0.005$ uncorrected for multiple comparisons. Activations with cluster size < 5 are not listed. Coordinates are listed in MNI space. ext, extending; L, left; R, right.

comparison of close – far trials (*peak coordinates* 69, −22, 28; $t = 3.35$; *cluster size* = 11).

Next, we performed conjunction analyses at the whole-brain level between our congruency interference (i.e., incongruent-control and incongruent-congruent) and physical size difference effect (i.e., close – far) contrasts at $p < 0.005$ uncorrected for multiple comparisons (Table 6; Fig. 6). There were no shared voxels within any region of DS in these two conjunction analyses, even with a liberal statistical threshold of $p < 0.05$ uncorrected for multiple comparisons. Of note, voxels within left ACC were common to both our incongruent – congruent and close – far contrasts, as were voxels within bilateral supramarginal gyrus, supporting our contention that both types of interference were equally cognitively effortful.

We next completed a disjunction analysis by applying an exclusive mask of BOLD signal in our close – far contrast ($p < 0.005$ uncorrected for multiple comparisons) to our incongruent – congruent contrast ($p < 0.005$ uncorrected for multiple comparisons) to critically test whether DS BOLD signal is significantly increased in our congruency contrast relative to DS BOLD signal in our distance contrast (Table 7; Fig. 7a). A significant activation originating in right thalamus (*peak coordinates* 18, −7, 16; $t_{(1, 90)} = 3.08$; *cluster size* = 51) that extended into right dorsal caudate and a secondary activation in right dorsal putamen (*peak coordinates* 27, 7, −1; $t_{(1, 90)} = 3.51$) from a larger cluster originating in the right postcentral gyrus (*peak coordinates* 66, −7, 13; $t_{(1, 90)} = 4.76$; *cluster size* = 1881) were seen. These results support the contention that DS is implicated specifically when cognitive control demands increase (i.e., incongruent – congruent) and not merely with enhanced cognitive effort. We repeated this exclusive masking

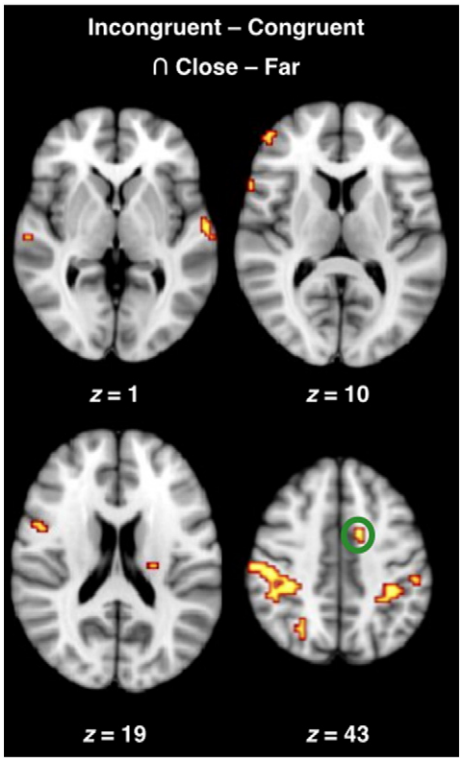

Fig. 6. Axial slices showing significant activations from our conjunction analysis. No shared voxels were present in DS. Shared voxels seen within ACC are circled in green at $z = 43$ ($p < 0.005$ uncorrected for multiple comparisons).

Table 7
Disjunction analyses of our incongruent – congruent and close – far contrasts.

Contrast	Anatomical Region	Coordinates (*x*, *y*, *z*)	*t*-stat	Cluster size
incongruent – congruent masked with close – far	**R thalamus (ext. into dorsal caudate)**	**18, −7, 16**	**3.08**	**51**
	R postcentral gyrus	66, −7, 13	4.76	1881
	(R dorsal putamen)	**27, −7, 1**	**3.51**	*
	L superior temporal gyrus	−60, −4, 1	4.62	568
	L postcentral gyrus	−33, −34, 46	4.35	427
	L lingual gyrus	−18, −58, −17	4.32	126
		0, −70, 7	3.01	14
		−15, −46, −5	2.96	25
	R hippocampus	21, −25, −11	4.17	445
	R frontal orbital cortex	18, 32, −17	4.16	39
		30, 29, 10	3.46	20
	L/R occipital pole	0, −91, 22	3.79	67
	L insular cortex	−39, 2, −17	3.72	18
	L hippocampus	−21, −19, −11	3.60	34
	L juxtapositional lobule cortex	−12, −1, 43	3.56	94
	R dorsolateral prefrontal cortex	39, 44, 28	3.54	120
	R inferior temporal gyrus	48, −22, −23	3.45	14
		54, −43, −14	3.05	7
	R thalamus	12, −19, 4	3.37	23
	L temporal fusiform cortex	−42, −28, −17	3.29	14
	R posterior cingulate gyrus	3, −43, 4	3.13	13
	L middle frontal gyrus	−39, 38, 34	3.12	12
	R supramarginal gyrus	48, −43, 43	3.10	6
	L supramarginal gyrus	−36, −49, 19	3.07	8
	R temporal occipital fusiform cortex	24, −61, −14	3.02	37
	L thalamus	−18, −31, 4	2.98	10
	R inferior frontal sulcus	48, 41, 4	2.97	5
	R intracalcarine cortex	24, −61, 10	2.78	11
close – far masked with incongruent – congruent	R inferior temporal gyrus	51, −58, −14	5.51	1357
	L inferior temporal gyrus	−45, −55, −8	5.45	778
	R precentral gyrus	45, 8, 25	5.44	513
	L precentral gyrus	−45, 2, 28	5.42	280
	R ventrolateral prefrontal cortex	48, 38, 16	4.79	212
	L superior parietal lobule	−27, −55, 49	4.24	360
	L white matter (ext. into lingual gyrus)	−3, −73, −23	4.21	85
	L juxtapositional lobule	−15, 2, 40	3.82	60
	R orbitofrontal cortex	21, 47, −14	3.41	14
	L middle frontal gyrus	−45, 35, 19	3.20	44
	L orbitofrontal cortex	−45, 47, −14	2.92	5
	R postcentral gyrus	6, −37, 61	2.88	7
	L supramarginal gyrus	−57, −28, 46	2.87	7
	R superior temporal gyrus	60, −22, −2	2.85	9
	R white matter	15, 26, 7	2.72	5

Contrasts and exclusive masks were thresholded at $p < 0.005$ uncorrected for multiple comparisons. Activations of cluster size > 5 that remained after masking are listed above. Coordinates are listed in MNI space. L, left; R, right.

procedure by masking out BOLD signal in our incongruent – congruent contrast ($p < 0.005$ uncorrected for multiple comparisons) from our close – far contrast ($p < 0.005$ uncorrected for multiple comparisons). No preferential activity was seen in DS (Fig. 7b). To further bolster our contention that DS mediates cognitive control and not cognitive effort *per se*, we repeated our first disjunction analysis by applying an exclusive mask of BOLD signal in our close – far contrast ($p < 0.05$ uncorrected for multiple comparisons) to our incongruent – congruent contrast ($p < 0.05$ with FDR correction). Even with these much more stringent statistical thresholds, activations in right dorsal caudate (*peak coordinates* 18, −10, 19; $t_{(1, 90)} = 2.93$; *cluster size* = 9), left dorsal caudate (*peak coordinates* −18, −4, 19; $t_{(1, 90)} = 2.85$; *cluster size* = 2), as well as a secondary activation in right dorsal putamen (*peak coordinates* 27, −7, 1; $t_{(1, 90)} = 3.51$) from a larger cluster originating in right postcentral gyrus (*peak coordinates* 66, −7, 13; $t_{(1, 90)} = 4.76$; *cluster size* = 1351) were seen (Table 8; Fig. 7c). Taken together, the results of our disjunction analyses provide clear evidence that DS is *more active* due to elevated cognitive control demands and not simply due to the need for more cognitively effortful processing *per se*.

We followed with ROI analyses to investigate DS using our incongruent – congruent and close – far contrasts (Fig. 8). In the incongruent – congruent contrast, we found significant mean signal change in right DS ($t = 3.07$; $p = 0.005$). For our close – far contrast, no significant activations were noted in the DS ROIs (left: $t = 1.38$; $p = 0.30$; right: $t = 1.63$; $p = 0.20$). The magnitude of mean signal change in right DS in our incongruent – congruent and close – far contrasts did not differ significantly ($t = 0.38$; $p = 0.49$) using a paired t-test. We also found significant, common bilateral mean signal change in the ACC ROI for the interference contrast (left: $t = 3.71$; $p < 0.01$ right: $t = 2.98$; $p = 0.001$) as well as left ACC in the close – far contrast (left: $t = 2.36$; $p < 0.05$).

Finally, brain-behaviour correlations of BOLD signal with Stroop interference (i.e., incongruent – congruent; incongruent – control) as well as with close – far physical size difference scores were performed at $p < 0.005$ uncorrected for multiple comparisons (Table 9). We found that dorsal caudate BOLD signal was negatively correlated with interference scores in both our Stroop interference contrasts (i.e., incongruent - congruent; incongruent – control), demonstrating its role in cognitive control (Fig. 9). We found no correlation between DS BOLD signal and difference scores for our close – far contrast, even at $p < 0.05$ uncorrected for multiple comparisons. We also found no correlation between ACC BOLD signal and RTs in any of our contrasts. Left supramarginal gyrus BOLD signal was positively correlated with interference scores for both our interference contrasts.

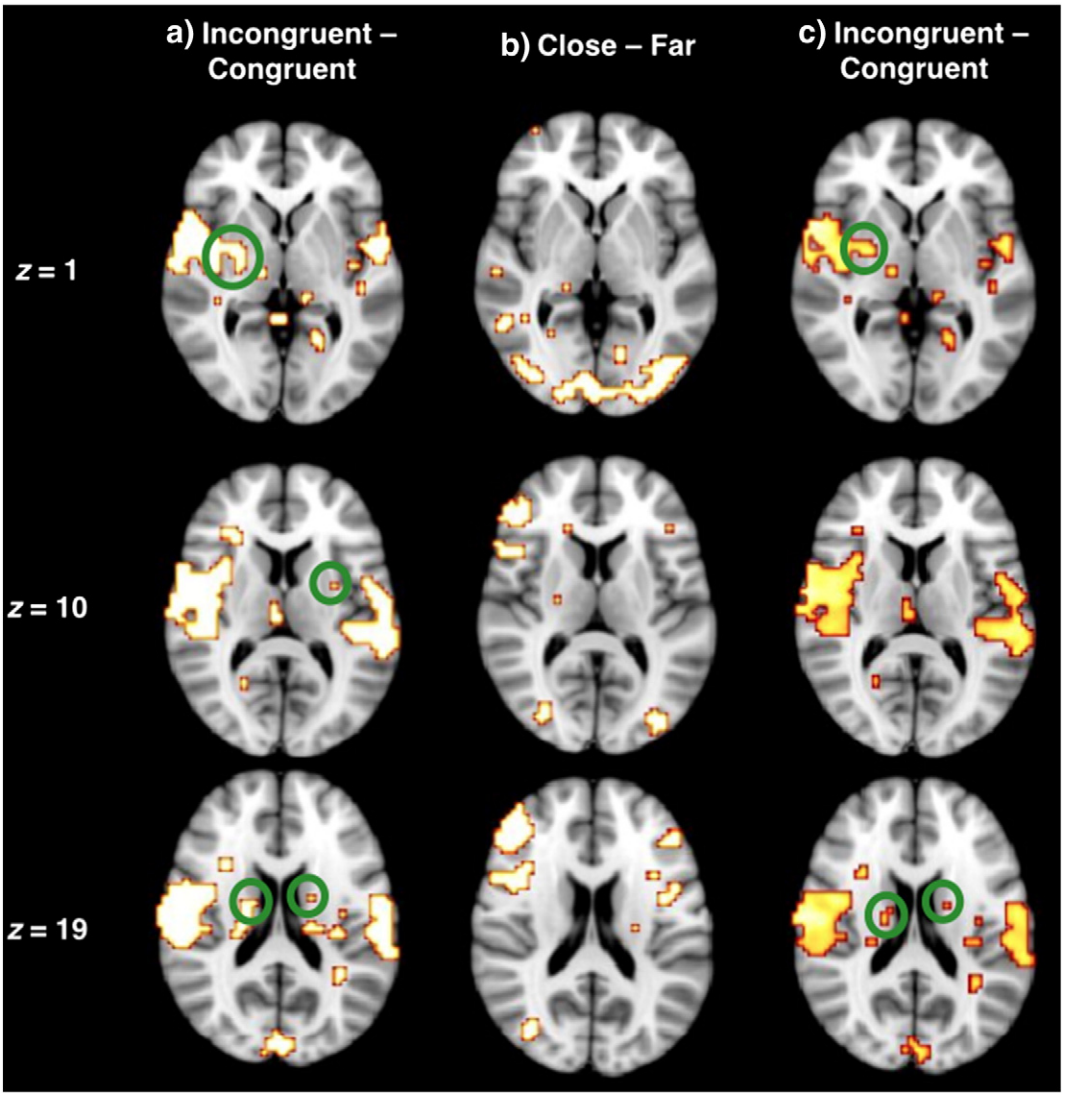

Fig. 7. Axial slices showing significant activations for disjunction analyses. Column a) shows significant voxels in our incongruent – congruent contrast ($p < 0.005$ uncorrected for multiple comparisons) after masking out activations in our close – far contrast ($p < 0.005$ uncorrected for multiple comparisons). Column b) shows significant voxels in our close – far contrast ($p < 0.005$ uncorrected for multiple comparisons) after masking out activations in our incongruent – congruent contrast ($p < 0.005$ uncorrected for multiple comparisons). Column c) shows significant voxels in our incongruent – congruent contrast ($p < 0.05$ with FDR correction) after masking out activations in our close – far contrast ($p < 0.05$ uncorrected for multiple comparisons). This more stringent disjunction analysis was performed to further bolster our contention that DS mediates cognitive control and not cognitive effort *per se*. Significant activations in DS for each disjunction analysis are circled in green.

Discussion

Using a number Stroop task with simultaneous fMRI, we examined whether DS mediates cognitive control processes specifically or cognitive effort generally. The physical size difference between number pairs on the relevant dimension and the numerical magnitude difference between number pairs on the irrelevant dimension were fully crossed with congruency, such that these effects were entirely orthogonal. In this way, we were able to examine the effect of congruency and physical size difference effects on RTs, error rates, and fMRI BOLD signal *within the same data set*. We hypothesized that our congruency manipulation (incongruent vs. congruent or control) stresses cognitive control processes as well as increases cognitive effort demands. In contrast, the physical distance effect (i.e., close 15 point font differences vs. far 45 point font differences) enhances the cognitive effort required to select the larger number of the pair, but does not require additional cognitive control.

Participants took longer to respond and had higher error rates during incongruent relative to congruent and control trials, and for close relative to far physical size difference trials. Participants responded faster during congruent trials relative to control trials. These findings are consistent with a very large literature (Dyer, 1973; Jensen and Rohwer, 1966; Macleod, 1991; MacLeod and MacDonald, 2000; Holloway and Ansari, 2010; Kaufmann et al., 2005). Congruency, physical size, and numerical magnitude difference variables did not interact.

Analogous to our behavioural analyses, we investigated the effects of congruency (incongruent vs. congruent vs. control) and physical size differences (close vs. far) on BOLD signal. We found that DS activity was modulated by our congruency variable. Pairwise comparisons revealed greater DS activation for incongruent trials—during which conflicting information on the irrelevant dimension needed to be suppressed—compared to the congruent case. At a slightly more liberal criterion ($p < 0.005$ uncorrected for multiple comparisons), these same DS regions were also significantly more active for incongruent compared to control trials. No striatal regions were preferentially more active for control or congruent trials relative to incongruent trials. Of greater significance given our aims, preferential DS activation did not occur for close relative to far physical size difference comparisons or the reverse contrast. Even using a very liberal criterion of $p < 0.05$,

Table 8
Additional stringent disjunction analysis of our incongruent – congruent masked with our close – far contrast.

Contrast	Anatomical Region	Coordinates (*x*, *y*, *z*)	*t*-stat	Cluster size
incongruent – congruent masked with close – far	**R dorsal caudate**	**18, −10, 19**	**2.93**	**9**
	L dorsal caudate	**−18, −4, 19**	**2.85**	**2**
	R postcentral gyrus	66, −7, 13	4.76	1351
	(R dorsal putamen)	(**27, −7, 1**)	(**3.51**)	*
		33, −28, 40	3.91	11
		54, −22, 58	2.72	1
	L lingual gyrus	−18, −58, −17	4.32	81
		−15, −46, −5	2.96	24
	L postcentral gyrus	−42, −25, 40	4.24	91
		−36, −28, 58	3.01	13
	R hippocampus	21, −25, −11	4.17	421
	R orbitofrontal cortex	18, 32, −17	4.16	11
		30, 38, −17	3.43	5
	L central opercular cortex	−57, −1, 4	3.97	507
	L/R cuneal cortex	0, −88, 25	3.77	43
	L insular cortex	−39, 2, −17	3.72	17
	L posterior cingulate gyrus	−15, −25, 34	3.68	120
	L hippocampus	−21, −19, −11	3.60	35
	R inferior temporal gyrus	48, −22, −23	3.45	14
		54, −40, −14	2.82	2
	R dorsolateral prefrontal cortex	27, 47, 37	3.43	75
	R posterior cingulate gyrus	15, −31, 37	3.42	134
		6, −43, 4	2.94	4
		3, −34, 28	2.82	4
	R thalamus	12, −16, 4	3.33	19
		21, −31, 7	2.78	1
	L temporal fusiform cortex	−42, −28, −17	3.29	14
	L anterior cingulate gyrus	−9, −1, 40	3.27	64
	R inferior frontal gyrus	33, 29, 10	3.24	2
	R supramarginal gyrus	69, −34, 31	3.22	2
	L middle frontal gyrus	−39, 38, 34	3.12	12
	L juxtapositional lobule cortex	−15, 5, 49	3.11	4
	L supramarginal gyrus	−36, −49, 19	3.07	8
		−51, −37, 43	2.82	2
		−51, −31, 34	2.75	3
	L/R lingual gyrus	0, −70, 7	3.01	9
	L thalamus	−18, −31, 4	2.98	10
		−18, −22, 16	2.64	1
	R temporal fusiform cortex	39, −13, −23	2.85	3
	R precuneus cortex	12, −79, 43	2.84	4
		3, −49, 61	2.67	2
		18, −67, 43	2.64	1
	L subcallosal cortex	−12, 17, −11	2.79	3
	R intracalcarine cortex	24, −61, 10	2.78	6
	R lingual gyrus	6, −73, −8	2.77	3
		12, −88, −11	2.73	1
	R temporal occipital fusiform cortex	24, −61, −11	2.72	1
	R precentral gyrus	21, −25, 58	2.71	1
	R occipital fusiform gyrus	24, −67, −14	2.67	3
	L lateral occipital cortex	−57, −67, −2	2.67	1

Incongruent – congruent contrast was thresholded at $p < 0.05$ with FDR correction and an exclusive mask of our close – far contrast at $p < 0.05$ uncorrected for multiple comparisons was applied. Activations that remained after masking are listed above. Coordinates are listed in MNI space. L, left; R, right.

uncorrected for multiple comparisons at the whole-brain level, no DS peaks of 10 contiguous voxels or greater were detected for our close – far contrast.

In contrast, ACC was significant in our main effect analyses of both congruency and physical size differences, as well as during subsequent pairwise comparisons of incongruent – congruent and close – far trials. The supramarginal gyrus was significant for the main effect of physical size difference and pairwise comparisons of incongruent – congruent and close – far contrasts. These activations confirm that our aim of modulating cognitive effort using both congruency and physical size difference manipulations was achieved.

Conjunction analyses – completed using a slightly more liberal criterion ($p < 0.005$ uncorrected for multiple comparisons) – between our congruency interference (i.e., incongruent – congruent, incongruent – control) contrasts yielded shared voxels within DS. In contrast, our congruency-related interference and physical size (i.e., close-far) conjunction analyses revealed no shared voxels in DS. However, left ACC activation was shared between our incongruent – congruent and close – far contrasts, and bilateral supramarginal gyrus activation was common for incongruent – congruent or incongruent – control and our close – far contrast. This supports the claim that we succeeded in creating conditions that were equally effortful using congruency and physical size difference manipulations.

Disjunction analysis – performed by masking out all voxels arising in our close – far contrast ($p < 0.005$ uncorrected for multiple comparisons) from our incongruent – congruent contrast ($p < 0.005$ uncorrected for multiple comparisons) – yielded significant voxels in right dorsal caudate and a secondary activation in right dorsal putamen. Repeating this analysis with much more stringent thresholds (incongruent – congruent contrast at $p < 0.05$ with FDR correction masked with close – far contrast at $p < 0.05$ uncorrected for multiple comparisons) yielded significant bilateral dorsal caudate activations as well as a secondary activation in right dorsal putamen. These results provide direct evidence that DS is significantly more active for interference contrasts related to elevated cognitive control demands than for interference occurring due to closer physical size comparisons. Disjunction analysis, completed by masking out all voxels arising in our incongruent – congruent contrast ($p < 0.005$ uncorrected for multiple comparisons) from our close – far contrast ($p < 0.005$ uncorrected for multiple comparisons) yielded no significant voxels in DS, lending further credence to our contention that DS mediates cognitive control and not cognitive effort *per se*.

ROI analyses yielded results consistent with our whole-brain analyses. Significant mean signal change was found in right DS in our incongruent – congruent contrast, but no mean signal change was found within our DS ROIs for the close – far contrast. The difference in the magnitude of signal change in right DS in our incongruent – congruent and close – far contrasts did not reach significance; however, despite this finding, our disjunction analyses surveying the whole brain – and reported above – did uncover preferentially more bilateral DS activity in the congruency relative to distance contrasts. No voxels in DS were significantly more active for the physical size distance effect compared to the congruency effect. As expected, and a demonstration of our success in matching the effort required by our congruency and distance manipulations, significant mean signal changes were seen in our ACC ROIs for both interference and close – far contrasts.

Finally, brain-behaviour investigations – completed using a slightly more liberal criterion ($p < 0.005$ uncorrected for multiple comparisons) – revealed that DS BOLD signal was negatively correlated with Stroop interference scores, but close – far physical difference scores did not correlate with DS BOLD signal in any manner. That is, higher BOLD signal in DS was associated with less interference from the distracting dimension, as would be expected for a brain region that is implicated in cognitive control functions. ACC BOLD signal was not correlated with RTs in any of our contrasts though left supramarginal gyrus BOLD was positively correlated with interference and difference scores in both our interference and distance contrasts, respectively. Taken together, we conclude that DS plays a role specifically in cognitive control and not in cognitively effortful processing *per se*.

DS in cognitive control or cognitive effort

Preferential DS activation for incongruent relative to congruent and control Stroop trials has been noted previously (Ali et al., 2010; Ansari

Table 9
Positive and negative correlations between BOLD signals and RTs in our interference and close – far contrasts.

Correlation	Type	Anatomical region	Coordinates (*x*, *y*, *z*)	*t*-stat	Cluster size
incongruent – congruent	positive	R insular cortex	36, 2, 1	4.46	11
		L supramarginal gyrus	−57, −43, 49	4.02	5
		R inferior frontal gyrus	48, 23, 4	3.89	23
			57, 17, 10	3.74	6
		R middle temporal gyrus	60, −43, 13	3.35	5
		R dorsolateral prefrontal cortex	39, 50, 31	3.33	5
	negative	**L dorsal caudate**	**−18, −7, 22**	**3.85**	**7**
		R thalamus	6, −4, 19	6.44	33
			−6, −25, 19	4.16	10
		L/R precuneus	0, −64, 31	5.04	43
		L middle temporal gyrus	−57, −13, −17	4.36	14
		R amygdala	27, −13, −11	4.29	25
		R thalamus	18, −16, 13	4.18	5
		R temporal pole	39, 14, −26	4.15	17
		L inferior temporal gyrus	−45, −16, −26	3.98	5
		L frontal orbital cortex	−39, 32, −14	3.35	8
incongruent – control	positive	R dorsolateral prefrontal cortex	39, 50, 31	3.95	6
		L superior parietal lobule	−39, −40, 58	3.95	16
			−27, −58, 52	3.52	24
		R inferior frontal gyrus	60, 23, 10	3.94	9
		L frontal orbital cortex	−51, 26, −5	3.64	9
		L supramarginal gyrus	−54, −43, 49	3.57	7
		L middle frontal gyrus	−42, 8, 40	3.51	18
		R lateral occipital cortex	27, −85, 1	3.20	5
	negative	**R dorsal caudate**	**18, −13, 25**	**3.37**	**10**
		R amygdala	24, −13, −11	4.75	21
		L/R white matter (ext. to thalamus)	0, −28, 13	4.24	14
close – far	positive	L precuneus	−12, −43, 46	4.41	18
		L lateral occipital cortex	−30, −85, 25	4.34	102
		L precentral gyrus	−39, −7, 34	4.15	8
		L central opercular cortex	−60, −13, 13	3.50	6
		L superior parietal cortex	−27, −58, 58	3.38	7
	negative	L dorsolateral prefrontal cortex	−15, 47, 31	3.72	13

All *t* values listed above were found at $p < 0.005$ uncorrected for multiple comparisons. Activations with cluster size < 5 are not listed. Coordinates are listed in MNI space. ext, extending; L, left; R, right.

et al., 2006; Tang et al., 2009; Peterson et al., 1999, 2002; Pardo et al., 1990). Similarly, DS is preferentially active in shifting from one goal to another (Grahn et al., 2008; Hazy et al., 2006; Vakil et al., 2004), in resolving incongruent stimulus-stimulus associations that conflict across consecutive trials (MacDonald et al., 2011), as well as in switching among decision strategies (Benke et al., 2003: Cameron et al., 2010; Ell et al., 2006; Grahn et al., 2008; Leber et al., 2008; Yehene et al., 2008). These findings, and ours reported here, can be interpreted as evidence for DS' role in cognitive control processes because correct responding requires suppressing competing responses, shifting attention from salient but irrelevant stimulus dimensions to target dimensions, or overcoming previously established associations. Keeping in mind that cognitive effort has been defined as the proportion of engaged, limited-capacity central processing (Russo and Dosher, 1983), the number of elementary processes enacted (Bettman et al., 1990), or the duration over which cognitive resources are expended (Christensen-Szalanski, 1980), these condition that stress cognitive control mechanisms are also more cognitively effortful than their comparison conditions. This introduces an alternative explanation for increased DS BOLD signal in these conditions.

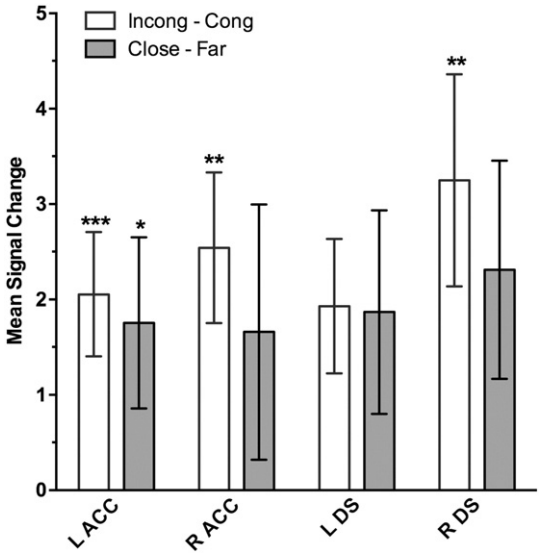

Fig. 8. Mean signal change for regions of interest in our incongruent – congruent and close – far contrasts. A single asterisk denotes significant mean signal change at $p < 0.05$. Double asterisks denote significant mean signal change at $p < 0.01$. Triple asterisks denote mean signal change at $p < 0.001$. ACC, anterior cingulate cortex; Cong, congruent; DS, dorsal striatum; Incong, incongruent; L, left; R, right.

To differentiate cognitive control from cognitive effort we also investigated the effect of physical size differences between number pairs using the same data set. In line with a number of similar studies, RTs were longer for close relative to far physical size differences between number pairs, which is consistent with the view that these trials are more cognitively effortful (Cohen Kadosh et al., 2005; Kaufmann et al., 2005, 2006; MacDonald et al., 2014; Pinel et al., 2001). However, varying the physical size differences between number pairs does not alter cognitive control demands. That is, close and far trials do not differ in their requirement to shift attention from one stimulus dimension to another, or override more automatic or habitual response tendencies (Botvinick et al., 2001; Cools and D'Esposito, 2011; Liu et al., 2004; MacDonald et al., 2000). DS activity did not correlate with the behavioural slow-down in responding for number pairs that had smaller physical size differences compared to those with larger differences, even when a liberal statistical threshold was employed. We interpret these findings as support for the notion that DS does not merely mediate cognitive effort, but rather is specifically engaged in decisions that

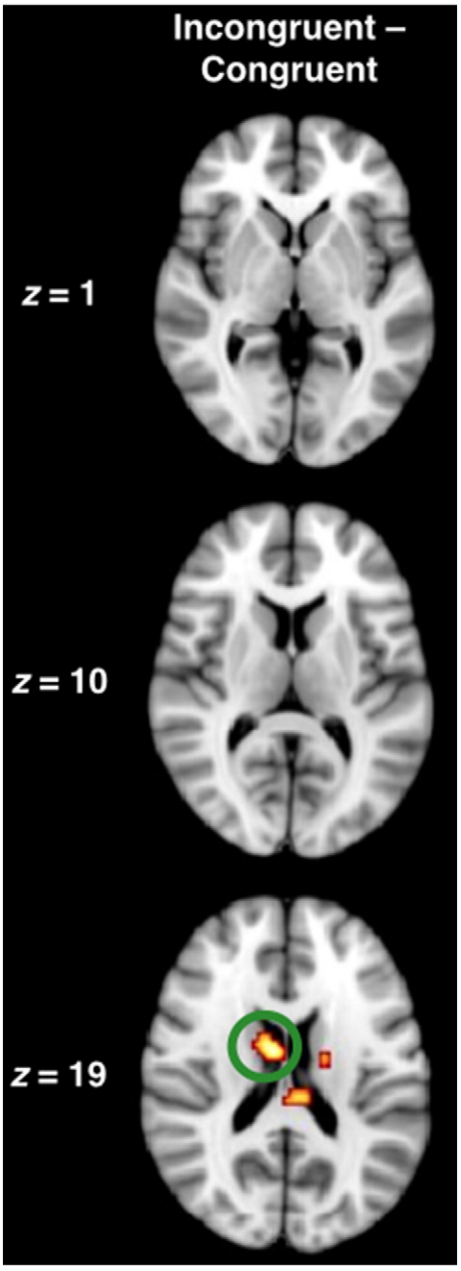

Fig. 9. Axial slices showing significant activations for negative BOLD-Stroop Interference correlations. Significant activations ($p < 0.005$ uncorrected for multiple comparisons) in DS are circled in green.

require greater deliberation or cognitive control. The fact that DS BOLD signal was negatively correlated with the magnitude of the Stroop interference effect further suggests its role in cognitive control, though this was only significant at $p < 0.005$ uncorrected for multiple comparisons. When DS BOLD signal was reduced, the irrelevant and distracting dimension interfered more with responding. Conversely, When DS BOLD signal was increased, responding was more focused and less susceptible to distraction.

Weaknesses and alternative interpretations of the current study addressed

An inherent difficulty in our approach is that to refute the possibility that DS mediates cognitive effort requires accepting a null hypothesis in our main analyses. In a well-designed study, *rejecting* the null hypothesis warrants confidence that differences between conditions arose due to manipulation of the experimental variable. Conclusions drawn from *failing to reject* the null hypothesis are fraught with greater difficulty. Statistical equivalence between conditions could arise due to unsuccessful implementation of the critical experimental manipulation or due to insufficient power to detect *true* differences between the contrasted conditions. To mitigate this criticism of our main analyses, however, we found significant differences in the DS BOLD response for the incongruent - congruent contrast relative to the close – far contrast using exclusive masking. That is, DS activations in the former contrast were unique and significantly greater than for the latter, and consequently our conclusions about differential DS involvement in congruency versus distance effects do not rest solely on a null result. It should be noted that the pairwise comparisons of beta values in our caudate ROI between congruency and distance contrasts did not, however, reach significance. Finally, the converse disjunction analysis – completed using more lenient statistical thresholds – revealed no significant DS BOLD signal for the close – far contrast relative to the incongruent – control comparison.

Additional considerations further mollify concerns about interpreting the null effect in the main close – far distance analyses. A number of findings suggest that we succeeded in critically testing DS' role in cognitive effort. Though we failed to find differential DS BOLD signal between number pairs with smaller versus larger physical size differences, the predicted behavioural differences arose and the pattern of cortical activations associated with variation in physical size differences in the current study was coherent with the existing literature (e.g., ACC, supramarginal gyrus extending to the intraparietal sulcus, left superior parietal lobule, bilateral precuneus, left posterior cingulate gyrus; Ansari et al., 2005; Cohen Kadosh et al., 2005; Kaufmann et al., 2005, 2006; MacDonald et al., 2014; Pinel et al., 2001, 2004). Further, the behavioural interference effects from our congruency manipulation (i.e., incongruent – control, incongruent – congruent) and our physical size difference effect (i.e., close minus far physical size difference number pairs) were not significantly different at $p < 0.05$. The interference effects for incongruent – control was 53.59 ± 8.48 (ms ± SEM) and incongruent – congruent was 68.57 ± 8.04 (ms ± SEM). These values were comparable to the interference achieved for close – far physical size difference trials, 67.98 ± 16.80 (ms ± SEM). This is important because it suggests that at the behavioural level, our congruency and size manipulations were equally robust, and the cognitive effort required was comparable for both experimental conditions relative to their respective baseline conditions. In line with this finding, the activations seen at the border of the juxtapositional lobule cortex and ACC were present during pairwise comparisons and conjunction analyses of interference and physical size contrasts, in line with ACC's role in attentional and effortful processing (Shenhav et al., 2013; Ansari et al., 2006; Bench et al., 1993; Botvinick et al., 2001; Carter et al., 1995; but see Kaufmann et al., 2005; Tang et al., 2009 for notable negative examples). These ACC activations are also known to vary both in the location of their local maxima and cluster sizes between studies (Egner and Hirsch, 2005). Common activation for interference and physical size distance effects in supramarginal gyrus was also expected and previously noted, given this region's role in stimulus-level attention and number comparison and processing (Kaufmann et al., 2005). In summary, this pattern of results suggests that we properly enacted our distance manipulation, and equated our Stroop and distance effects in terms of potency and required effort based on both behavioural and neural data. Our findings are therefore quite compelling and credible in refuting claims that DS merely mediates cognitive effort (Boehler et al., 2011; Krebs et al., 2012; Schmidt et al., 2012), converging with a larger literature using other methodologies that bear brief interpretation respecting DS and cognitive effort below.

The behavioural indices of increased cognitive effort are increased RTs and error rates studied in both humans (e.g., Moyer and Landauer, 1967) and animals (Dehaene et al., 1998). Our finding that preferential DS activity does not result for discriminations of more similar relative to more dissimilar stimuli has been found by others in both adults (Cohen Kadosh et al., 2005; MacDonald et al., 2014; Pinel et al., 2001, 2004) and

children (Kaufmann et al., 2006). Also in line with our findings, Zamarian et al. (2006) demonstrated that PD patients without dementia perform as well as healthy controls during tasks that involve working with analog magnitude scales (1–100), verbal counting, or single-digit magnitude comparisons—all tasks that vary cognitive effort leaving cognitive control processes invariant. Further, in MacDonald et al. (2014), PD patients and healthy controls were instructed to select the numerically larger or smaller written integer from a pair (e.g., one vs. eight) based on a simultaneously presented cue. All participants revealed a symbolic distance effect, whereby responses to number pairs that were closer (e.g., one vs. two) relative to farther (e.g., one vs. six) in numerical value were slower and more error prone. Of crucial importance, the symbolic distance effect for PD patients did not differ from that of healthy age-matched controls. Further, the symbolic distance effect was not affected by dopaminergic medication status (OFF vs. ON) of PD patients. This is inconsistent with a role for DS in mediating these effects, given that off medication in PD, DS function is compromised, whereas it is improved with dopamine replacement (Cools, 2006a; Shook et al., 2005; Hood et al., 2007; MacDonald et al., 2011). In similar fashion, numerous single-case studies of patients with basal ganglia lesions show no deficits in their ability to judge magnitude in the absence of conflict (Benke et al., 2003; Dehaene and Cohen, 1997; Delazer et al., 2004; Hittmair-Delazer et al., 1994). Taken together, converging evidence suggests that DS does not mediate cognitively effortful judgment or decisions *per se*.

DS in decision-making

Our findings cohere with mounting evidence from our lab (Hiebert et al., 2014a, 2014b; Vo et al., 2014), as well as a larger literature (e.g., Cools, 2006b; Cools et al., 2010; Grahn et al., 2008; Hughes et al., 2013). DS dysfunction in both humans and non-human primates results in deficits in shifting attention between stimuli, especially away from more salient ones (Benke et al., 2003; Cools et al., 2003, 2010; Thoma et al., 2008), flexibly altering decision-making strategies or response sets (Benke et al., 2003: Cameron et al., 2010; Ell et al., 2006; Grahn et al., 2008; Leber et al., 2008; Yehene et al., 2008), suppressing more automatic responses (Benke et al., 2003; Cameron et al., 2010; MacDonald et al., 2011; White, 2009), and updating goals (Grahn et al., 2008; Hazy et al., 2006; Vakil et al., 2004). In Thoma et al. (2008), patients with basal ganglia lesions showed increased RTs and error rates during the classical colour-word Stroop task. In PD patients, shifting attention to more salient stimuli is accomplished more easily (Cools et al., 2010; MacDonald et al., 2011), whereas shifting attention to less salient stimuli yields more impairment compared to controls (Cameron et al., 2010; Cools et al., 2006b, 2010; Hood et al., 2007; MacDonald et al., 2011). In healthy volunteers, DS activation occurs when participants are required to suppress competing motor responses, as in the incongruent condition of the Stroop task (Ali et al., 2010; Leung et al., 2000; Pardo et al., 1990; Pinel et al., 2004; Peterson et al., 1999, 2002). Taken together, these results suggest that DS is implicated in decision making when deliberation and cognitive control are required.

Conclusion

We used a simple number Stroop task to address a pervasive confound in the study of cognitive abilities mediated by DS. Cognitive effort usually increases proportionally with cognitive control demands. The number Stroop task allowed us to independently manipulate cognitive control and cognitive effort to investigate DS BOLD signal in relation to each of these separate cognitive effects. We found that increasing cognitive control requirements by introducing distracting, conflicting information (i.e., the incongruent case) increased participant RTs, error rates, and was associated with increased DS BOLD signal. Further, the magnitude of the DS BOLD signal was inversely correlated with the size of the Stroop effect, supporting its role in cognitive control. Enhancing cognitive effort demands by decreasing the difference in physical size between number pairs increased participant RTs, but was not associated with preferential DS activation, even using liberal statistical criteria. Our results support claims that DS specifically mediates cognitive control, and not cognitive effort *per se*, in decision-making. Increasingly, cognitive functions are ascribed to the striatum. Understanding these specific cognitive functions is important in anticipating cognitive and behavioural deficits of patients with neurological and psychiatric illnesses that implicate the striatum.

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References

Ali, N., Green, D.W., Kherif, F., Devlin, J.T., Price, C.J., 2010. The role of the left head of caudate in suppressing irrelevant words. J. Cogn. Neurosci. 22, 2369–2386.
Ansari, D., Garcia, N., Lucas, E., Hamon, K., Dhital, B., 2005. Neural correlates of symbolic number processing in children and adults. Neuroreport 16, 1769–1773.
Ansari, D., Fugelsang, J.A., Dhital, B., Venkatraman, V., 2006. Dissociating response conflict from numerical magnitude processing in the brain: an event-related fMRI study. NeuroImage 32, 799–805.
Beatty, W.W., Monson, N., 1996. Problem solving by patients with multiple sclerosis: comparison of performance on the Wisconsin and California Card Sorting Tests. J. Int. Neuropsychol. Soc. 2, 134–140.
Bench, C.J., Frith, C.D., Grasby, P.M., Friston, K.J., Paulesu, E., Frackowiak, R.S., Dolan, R.J., 1993. Investigations of the functional anatomy of attention using the Stroop test. Neuropsychologia 31, 907–922.
Benke, T., Delazer, M., Bartha, L., Auer, A., 2003. Basal ganglia lesions and the theory of fronto-subcortical loops: neuropsychological findings in two patients with left caudate lesions. Neurocase 9, 70–85.
Bettman, J.R., Johnson, E.J., Payne, J.W., 1990. A componential analysis of cognitive effort in choice. Organ. Behav. Hum. Decis. 45, 111–139.
Boehler, C.N., Hopf, J.M., Krebs, R.M., Stoppel, C.M., Shoenfield, M.A., Heinze, H.J., Noesselt, T., 2011. Task-load-dependent activation of dopaminergic midbrain areas in the absence of reward. J. Neurosci. 31, 4955–4961 (Mar).
Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.D., 2001. Conflict monitoring and cognitive control. Psychol. Rev. 108, 624–652.
Brand, N., Jolles, J., 1987. Information processing in depression and anxiety. Psychol. Med. 17, 145–153.
Butters, N., Rosvold, H.E., 1968. Effect of caudate and septal nuclei lesions on resistance to extinction and delayed-alternation. J. Comp. Physiol. Psychol. 65, 397–403.
Cameron, I.G., Watanabe, M., Pari, G., Munoz, D.P., 2010. Executive impairment in Parkinson's disease: response automaticity and task switching. Neuropsychoglia 48, 1948–1957 (2010).
Carter, C.S., Mintun, M., Cohen, J.D., 1995. Interference and facilitation effects during selective attention: an H215O PET study of Stroop task performance. NeuroImage 2, 264–272.
Chamberlain, S.R., Fineberg, N.A., Blackwell, A.D., Robbins, T.W., Sahakain, B.J., 2006. Motor inhibition and cognitive flexibility in obsessive-compulsive disorder and trichotillomania. Am. J. Psychiatr. 163, 1282–1284.
Christensen-Szalanski, J.J.J., 1980. A further examination of the selection of problem-solving strategies: The effects of deadlines and analytic aptitudes. Organ. Behav. Hum. Perform. 25, 107–122.
Cohen Kadosh, R., Henik, A., Rubensten, O., Mohr, H., Dori, H., van de Ven, V., Zorzi, M., Hendler, T., Goebel, R., Linden, D.E., 2005. Are numbers special? The comparison systems of the human brain investigated by fMRI. Neuropsychoglia 43, 1238–1248.
Cools, R., 2006a. Dopaminergic modulation of cognitive function-implications for L-DOPA treatment in Parkinson's disease. Neurosci. Behav. Rev. 30, 1–23.
Cools, R., D'Esposito, M., 2011. Inverted-U-shaped dopamine actions on human working memory and cognitive control. Biol. Psychiatry 69, 113–125.
Cools, R., Barker, R.A., Sahakian, B.J., Robbins, T.W., 2001. Mechanisms of cognitive set flexibility in Parkinson's disease. Brain 124, 2503–2512.
Cools, R., Barker, R.A., Sahakian, B.J., Robbins, T.W., 2003. L-Dopa medication remediates cognitive inflexibility, but increases impulsivity in patients with Parkinson's disease. Neuropsychologia 41, 1431–1441.
Cools, R., Ivry, R.B., D'Esposito, M., 2006b. The human striatum is necessary for responding to changes in stimulus relevance. J. Cogn. Neurosci. 18, 1973–1983.
Cools, R., Rogers, R., Barker, R.A., Robbins, T.W., 2010. Top-down attentional control in Parkinson's disease: salient considerations. J. Cogn. Neurosci. 22, 848–859.
Crofts, H.S., Dalley, J.W., Collins, P., Van Denderen, J.C., Everitt, B.J., Robbins, T.W., Roberts, A.C., 2001. Differential effects of 6-OHDA lesions of the frontal cortex and caudate nucleus on the ability to acquire an attentional set. Cereb. Cortex 11, 1015–1026.
Dehaene, S., Cohen, L., 1997. Cerebral pathways for calculation: double dissociation between rote verbal and quantitative knowledge of arithmetic. Cortex 33, 219–250.
Dehaene, S., Dehaene-Lambertz, G., Cohen, L., 1998. Abstract representations of numbers in the animal and the human brain. Trends Cogn. Neurosci. 21, 355–361.

Delazer, M., Domahs, F., Lochy, A., Karner, E., Benke, T., Poewe, W., 2004. Number processing and basal ganglia dysfunction: a single case study. Neuropsychologia 42, 1050–1062.
Divac, I., 1972. Neostriatum and functions of prefrontal cortex. Acta Neurobiol. Exp. (Wars) 32, 461–477.
Dyer, F.N., 1973. Interference and facilitation for color naming with separate bilateral presentations of the word and color. J. Exp. Psychol. 99, 314–317.
Egner, T., Hirsch, J., 2005. The neural correlates and functional integration of cognitive control in a Stroop task. NeuroImage 24, 539–547.
Ell, S.W., Marchant, N.L., Ivry, R.B., 2006. Focal putamen lesions impair learning in rule-based, but not information-integration categorization tasks. Neuropsychologia 44, 1737–1751.
Goldman, P.S., Rosvold, H.E., 1972. The effects of selective caudate lesions in infant and juvenile Rhesus monkeys. Brain Res. 43, 53–66.
Grahn, J.A., Parkinson, J.A., Owen, A.M., 2008. The cognitive functions of the caudate nucleus. Prog. Neurobiol. 86, 141–155.
Grinband, J., Hirsch, J., Ferrera, V.P., 2006. A neural representation of categorization uncertainty in the human brain. Neuron 49, 757–763.
Hayes, A.E., Davidson, M.C., Keele, S.W., Rafal, R.D., 1998. Toward a functional analysis of the basal ganglia. J. Cogn. Neurosci. 10, 178–198.
Hazy, T.E., Frank, M.J., O'Reilly, R.C., 2006. Banishing the homunculus: making working memory work. Neuroscience 139, 105–118.
Hiebert, N.M., Vo, A., Hampshire, A., Owen, A.M., Seergobin, K.N., MacDonald, P.A., 2014a. Striatum in stimulus-response learning via feedback and in decision making. NeuroImage 101, 448–457.
Hiebert, N.M., Seergobin, K.N., Vo, A., Ganjavi, H., MacDonald, P.A., 2014b. Dopaminergic therapy affects learning and impulsivity in Parkinson's disease. Ann. Clin. Transl. Neurol. 1, 833–843.
Hittmair-Delazer, M., Semenza, C., Denes, G., 1994. Concepts and facts in calculation. Brain 117, 715–728.
Holloway, I.D., Ansari, D., 2010. Developmental specialization in the right intraparietal sulcus for the abstract representation of numerical magnitude. J. Cogn. Neurosci. 22, 2627–2637.
Hood, A.J., Amador, S.C., Cain, A.E., Briand, K.A., Al-Refai, A.H., Schiess, M.C., Sereno, A.B., 2007. Levodopa slows prosaccades and improves antisaccades: an eye movement study in Parkinson's disease. J. Neurol. Neurosurg. Psychiatry 78, 565–570.
Hughes, L.E., Altena, E., Barker, R.A., Rowe, J.B., 2013. Perseveration and choice in Parkinson's disease: The impact of progressive frontostriatal dysfunction on action decisions. Cereb. Cortex 23, 1572–1581.
Humphries, M., Prescott, T., 2010. The ventral basal ganglia, a selection mechanism at the crossroads of space, strategy, and reward. Prog. Neurobiol. 90, 385–417.
Jensen, A.R., Rohwer, W.D., 1966. The Stroop wolor-word test: a review. Acta. Psychol. (Amst) 25, 36–93.
Kaufmann, L., Koppelstaetter, F., Delazer, M., Siedentopf, C., Rhomberg, P., Golaszewski, S., Felber, S., Ischebeck, A., 2005. Neural correlates of distance and congruity effects in a numerical Stroop task: an event-related fMRI study. NeuroImage 25, 888–898.
Kaufmann, L., Koppelstaetter, F., Siedentopf, C., Haala, I., Haberlandt, E., Zimmerhackl, L.B., Felber, S., Ischebeck, A., 2006. Neural correlates of the number-size interference task in children. Neuroreport 17, 587–591.
Krebs, R.M., Boehler, C.N., Roberts, K.C., Song, A.W., Woldorff, M.G., 2012. The involvement of the dopaminergic midbrain and cortico-striatal-thalamic circuits in the integration of reward prospect and attentional task demands. Cereb. Cortex 22, 607–615.
Leber, A.B., Turk-Browne, N.B., Chun, M.M., 2008. Neural predictors of moment-to-moment fluctuations in cognitive flexibility. Proc. Natl. Acad. Sci. U. S. A. 105, 13592–13597.
Leung, H.C., Skudlarski, P., Gatenby, J.C., Peterson, B.S., Gore, J.C., 2000. An event-related functional MRI study of the stroop color word interference task. Cereb. Cortex 10, 552–560.
Liu, X., Banich, M.T., Jacobson, B.L., Tanabe, J.L., 2004. Common and distinct neural substrates of attentional control in an integrated Simon and spatial Stroop task as assessed by event-related fMRI. NeuroImage 22, 1097–1106.
MacDonald, P.A., Monchi, O., 2011. Differential effects of dopaminergic therapies on dorsal and ventral striatum in Parkinson's disease: implications for cognitive function. Park. Dis. 572743.
MacDonald 3rd, A.W., Cohen, J.D., Stenger, V.A., Carter, C.S., 2000. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science 288, 1835–1838.
MacDonald, P.A., MacDonald, A.A., Seergobin, K.N., Tamjeedi, R., Ganjavi, H., Provost, J.S., Monchi, O., 2011. The effect of dopamine therapy on ventral and dorsal striatum-mediated cognition in Parkinson's disease: support from functional MRI. Brain 134, 1447–1463.
MacDonald, A.A., Seergobin, K.N., Tamjeedi, R., Owen, A.M., Provost, J.S., Monchi, O., Ganjavi, H., MacDonald, P.A., 2014. Examining dorsal striatum in cognitive effort using Parkinson's disease and fMRI. Ann. Clin. Transl. Neurol. 1, 390–400.
MacLeod, C., 1991. Half a century of research on the Stroop effect: An integrative review. Psychol. Bull. 109, 163–203.
Macleod, C.M., MacDonald, P.A., 2000. Interdimensional interference in the Stroop effect: uncovering the cognitive and neural anatomy of attention. Trends Cogn. Sci. 4, 383–391.
Monchi, O., Petrides, M., Petre, V., Worsley, K., Dagher, A., 2001. Wisconsin Card Sorting revisisted: distinct neural circuits participating in different stages of the task identified by event-related functional magnetic resonance imaging. J. Neurosci. 21, 7733–7741.
Monchi, O., Petrides, M., Strafella, A.P., Worsley, K.J., Doyon, J., 2006. Functional role of the basal ganglia in the planning and execution of actions. Ann. Neurol. 59, 257–264.
Moyer, R.S., Landauer, T.K., 1967. Time required for judgements of numerical inequality. Nature 215, 1519–1520.
Pardo, J.V., Pardo, P.J., Janer, K.W., Raichle, M.E., 1990. Role of the human anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. Proc. Natl. Acad. Sci. U. S. A. 87, 256–259.
Peterson, B.S., Skudlarski, P., Gatenby, J.C., Zhang, H., Anderson, A.W., Gore, J.C., 1999. An fMRI study of Stroop word-color interference: evidence for cingulate subregions subserving multiple distributed attentional systems. Biol. Psychiatry 45, 1237–1258.
Peterson, B.S., Kane, M.J., Alexander, G.M., Lacadie, C., Skudlarski, P., Leung, H.C., May, J., Gore, J.C., 2002. An event-related functional MRI study comparing interference effects in the Simon and Stroop tasks. Brain Res. Cogn. Brain Res. 13, 427–440.
Pinel, P., Dehaene, S., Riviere, D., LeBihan, D., 2001. Modulation of parietal activation by semantic distance in a number comparison task. NeuroImage 14, 1013–1026.
Pinel, P., Piazza, M., Le Bihan, D., Dehaene, S., 2004. Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. Neuron 41, 983–993.
Rogers, R.D., Andrews, T.C., Grasby, P.M., Brooks, D.J., Robbins, T.W., 2000. Contrasting cortical and subcortical activations produced by attentional-set shifting and reversal learning in humans. J. Cogn. Neurosci. 12, 142–162.
Rosvold, H.E., 1972. The frontal lobe system: cortical-subcortical interrelationships. Acta Neurobiol. Exp. (Wars) 32, 439–460.
Ruocco, A.C., 2005. The neuropsychology of borderline personality disorder: A meta-analysis and review. Psychiatry Res. 137, 191–202.
Russo, J.E., Dosher, B.A., 1983. Strategies for multiattribute binary choice. J. Exp. Psychol. 9, 676–696.
Schmidt, L., Lebreton, M., Clery-Melin, M.L., Daunizeau, J., Pessiglione, M., 2012. Neural mechanisms underlying motivation of mental versus physical effort. PLoS Biol. 10, e1001266.
Shenhav, A., Botvinick, M.M., Cohen, J.D., 2013. The expected value of control: an integrative theory of anterior cingulate cortex function. Neuron 79, 217–240.
Shook, S.K., Franz, E.A., Higginson, C.I., Wheelock, V.L., Sigvardt, K.A., 2005. Dopamine dependency of cognitive switching and response repetition effects in Parkinson's patients. Neuropsychologia 43, 1990–1999.
Tang, J., Critchley, H.D., Glaser, D.E., Dolan, R.J., Butterworth, B., 2009. Imaging informational conflict: a functional magnetic resonance imaging study of numerical stroop. J. Cogn. Neurosci. 18, 2049–2062.
Thoma, P., Koch, B., Heyder, K., Schwarz, M., Daum, I., 2008. Subcortical contributions to multitasking and response inhibition. Behav. Brain Res. 194, 214–222.
Vakil, E., Blachstein, H., Soroker, N., 2004. Differential effect of right and left basal ganglionic infarctions on procedural learning. Cogn. Behav. Neurol. 17, 62–73.
van Schouwenburg, M., Aarts, E., Cools, R., 2010. Dopaminergic modulation of cognitive control: distinct roles for the prefrontal cortex and the basal ganglia. Curr. Pharm. Des. 16, 2026–2032.
Vélez-van-Meerbeke, A., Zamora, I.P., Guzman, G., Figueroa, B., Lopez Cabra, C.A., Talero-Gutierrez, C., 2013. Evaluating executive function in schoolchildren with symptoms of attention deficit hyperactivity disorder. Neuroglia 28, 348–355.
Verte, S., Geurts, H.M., Roeyers, H., Oosterlaan, J., Sergeant, J.A., 2005. Executive functioning in children with autism and Tourette syndrome. Dev. Psychopathol. 17, 415–445.
Vo, A., Hiebert, N.M., Seergobin, K.N., Solcz, S., Partridge, A., MacDonald, P.A., 2014. Dopaminergic medication impairs feedback-based stimulus-response learning but not response selection in Parkinson's disease. Front. Hum. Neurosci. 8, 1–9.
Voorn, P., Vanderschuren, L., Groenewegen, H.J., Robbins, T.W., Pennartz, C., 2004. Putting a spin on the dorsal-ventral divide of the striatum. Trends Neurosci. 27, 468–474.
White, N.M., 2009. Some highlights of research on the effects of caudate nucleus lesions over the past 200 years. Behav. Brain Res. 199, 3–23.
Wickens, J., Budd, C., Hyland, B.I., Arbuthnott, G.W., 2007. Striatal contributions to reward and deision making: making sense of regional variations in a reiterating processing matrix. Ann. N. Y. Acad. Sci. 1104, 192–212.
Yehene, E., Meiran, N., Soroker, N., 2008. Basal ganglia play a unique role in task switching within the frontal- subcortical circuits: evidence from patients with focal lesions. J. Cogn. Neurosci. 20, 1079–1093.
Zamarian, L., Visani, P., Delazer, M., Seppi, K., Mair, K.J., Diem, A., Poewe, W., Benke, T., 2006. Parkinson's disease and arithmetics: the role of executive functions. J. Neurol. Sci. 248, 124–130.