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Note

Focal striatum lesions impair cautiousness in humans

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ABSTRACT

Functional neuroimaging data indicate the dorsal striatum is engaged when people are required to vary the cautiousness of their decisions, by emphasizing the speed or accuracy of responding in laboratory-based decision tasks. However, the functional contribution of the striatum to decision making is unknown. In the current study we tested patients with focal ischemic lesions of the dorsal striatum and matched non-lesion control participants on a speed-accuracy tradeoff (SAT) task. Analysis using a computational model of response selection in a competitive and time-pressured context indicated that the decisions of patients with striatal lesions were less cautious than those of matched controls. This deficit was most prominent when the accuracy of decisions was emphasized. The results are consistent with the hypothesis that the striatum plays an important role in strategically setting response caution, an essential function for flexible behavior.

1. Introduction

Some decisions require a snap judgment, while others require careful deliberation. People exhibit remarkable flexibility in their ability to optimize decision behavior in different contexts. The hallmark signature of this flexibility is the speed-accuracy tradeoff (SAT; Pachella, 1974; Reed, 1973; Wickelgren, 1977): the ability to shift between slow and careful decisions and fast but error prone responses. The SAT is thought to reflect a strategic setting of response caution: the decision maker selectively adjusts the amount of evidence

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they consider prior to committing to a course of action, where collecting a large amount of evidence corresponds to a high degree of response caution, and vice versa.

The SAT is typically studied in the laboratory with perceptual decision-making tasks that emphasize fast responding on some trials and careful responding on others. When participants are instructed to emphasize response speed over response accuracy, there is a larger blood-oxygen-level dependent (BOLD) response in the striatum and the pre-supplementary (pre-SMA) motor cortex (Forstmann et al., 2008; Ivanoff, Branning, & Marois, 2008; Van Maanen et al., 2011; Van Veen, Krug, & Carter, 2008; Winkel et al., 2012). One interpretation of the elevated BOLD response is an increase in baseline firing rates in these regions under speed-emphasis instructions. The additional input required to reach a neural threshold is therefore reduced, resulting in an effectively decreased level of response caution. In addition to functional imaging, anatomical measures of frontostriatal structural connectivity are positively correlated with the magnitude of individual participants' shift in response caution between speed- and accuracy-emphasis conditions (Forstmann et al., 2010). These data are consistent with models of basal ganglia function that emphasize a critical role for the striatum in response selection. Specifically, the basal ganglia are hypothesized to serve as a gate on cortical activation patterns, selectively releasing one or a limited set of responses from globally applied inhibition (Mink, 1996). Within this general framework, striatal dopamine has been hypothesized to provide the neurochemical basis for setting caution levels by altering striatal responsivity (Lo & Wang, 2006; Niv, Daw, & Joel, 2007; Robbins & Everitt, 2007; Winkel et al., 2012).

At a minimum, the imaging data indicate that striatal activity is sensitive to processes associated with setting and adjusting response caution. As with all imaging studies, however, the results are correlational. Stronger tests of functional hypotheses require that the striatum is not only active when decision makers set and adjust response caution, but that it is necessary or sufficient for such adjustment to take place. In one example of this approach, Ding and Gold (2012) showed that stimulating striatal neurons of non-human primates led to faster responses in the direction contralateral to the stimulation. This finding suggests that stimulation induced biased patterns of responding and thus altered response caution.

In the current study, we took a neuropsychological approach to test how focal lesions of the striatum affect performance on a SAT task. In particular, we compared patients with striatal lesions to matched controls on their ability to set and flexibly adjust response caution to meet changing task demands. To ensure that any observed group differences were not due to a global effect of 'general brain damage', we collected a large number of decision trials from each participant that allowed us to use a model-based analysis that separates the relative impact of response caution from general ability to complete the experimental task. We hypothesized that if the striatum is causally involved in setting the level of response caution, patients would have impaired levels of response caution relative to the controls. We additionally hypothesized that patients would show a reduced dynamic range in the level of caution between the speed- and accuracy-emphasis conditions.

2. Method

2.1. Participants

The institutional review board at the University of California, Berkeley, approved the experimental protocol. Five patients with chronic focal ischemic lesions in the dorsal striatum were recruited for the study. The patients were referred by neurologists in the San Francisco Bay area. To assess healthy cognitive functioning, all patients were tested on the Wechsler Adult Intelligence Scale (WAIS) IV (Wechsler, 2008), the Beck Depression Inventory (BDI) (Beck, Ward, Mendelson, Mock, & Erbaugh, 1961), and the National Adult Reading Test – Revised (NART-R) (Spreen & Strauss, 1998). Seven control participants were recruited in The Netherlands, selected to match the patients in terms of age and education. Table 1 provides a complete overview of the participants' demographics and neuropsychology.

The patients' lesions were reconstructed by registering their anatomical scans to a Montreal Neurological Institute template using a 7-parameter transformation (3D rotation, 3D translation, and global rescale) using FLIRT (Jenkinson, Bannister, Brady, & Smith, 2002; Jenkinson & Smith, 2001). The resulting reconstructions for the five patients are shown in Fig. 1. The lesions, while not always constrained to the striatum proper, all affected the putamen. The lesion of patient 2 extended along the claustrum and external capsule.

2.2. Experimental task

We used a modified version of the random dot motion task (Fig. 2A), a popular paradigm in visual neuroscience (Britten, Shadlen, Newsome, & Movshon, 1992; for details see; Forstmann et al., 2008). Speed-accuracy requirements were manipulated on a trial-by-trial basis. Each trial began with a cue that indicated whether the participant should respond on the upcoming trial quickly (speed trial) or accurately (accuracy trial). The cue remained visible for 1000 msec. The cue was then replaced by a fixation cross that remained visible for a randomly selected variable interval (50, 200, 500, or 800 msec). The random dot motion stimulus was then presented for 1500 msec. The motion stimulus consisted of thirty images that were each displayed for 50 msec. Each image contained 120 white dots on a black background. Sixty of these dots were redrawn in the next image, all of which were displaced to the left on 50% of the trials and to the right on the other 50% of the trials. This resulted in the percept of coherent motion to the left or right. The other sixty dots were redrawn in a random position, rendering the signal harder to detect. The set of dots to be redrawn was selected at random on each frame update, resulting in a 'lifetime' of 1 frame update for 30 dots on average, of 2 updates for 15 dots on average, and so on.

Participants indicated their response (left or right moving coherent motion) with a button press. Responses were given with the index and middle finger of the ipsilesional hand for patients and the dominant hand for controls. The response

Table 1 – Demographic and neuropsychological information for the participants.

Controls	Age	Education	MMSE	Gender
1	61	10	30	F
2	58	15	30	M
3	57	16	30	M
4	62	16	29	M
5	58	20	28	F
Mean (SD)	59.2 (2.2)	15.4 (3.6)	29.4 (.9)	

Patients	Age	Education	MMSE	Gender
1	67	14	29	M
2	59	16	29	M
3	59	18	29	F
4	51	12	27	M
5	73	14	28	M
Mean (SD)	61.8 (8.4)	14.8 (2.3)	28.4 (.9)	

Patients	Lesion		Handedness	
	Side	Time since	Pre	Post
1	L	17	R	L
2	R	8	R	R
3	L	6 & 16	R	L
4	L	Unknown	R	L
5	L	16	R	L

Patients	WAIS			
	VIQ	PIQ	FSIQ	WMI
1	111	97	104	97
2	103	98	101	111
3	113	117	113	97
4	74	79	75	78
5	119	107	115	113

Patients	NART-R (errors)	BDI Raw	BDI level
1	10	12	MINIMAL
2	22	6	MINIMAL
3	4	7	MINIMAL
4	25	1	MINIMAL
5	12	10	MINIMAL

MMSE – mini mental state examination. WAIS – Wechsler adult intelligence scale. IQ – intelligence quotient. VIQ – verbal IQ. PIQ – performance IQ. FSIQ – full scale IQ. WMI – working memory index. NART-R – national adult reading test – revised. BDI – Beck depression inventory.

time was defined as the interval from stimulus onset to registration of the button press. Following a response, feedback was presented for 300 msec: "correct" or "incorrect" on accuracy-emphasis trials, and "in time" (before the individualized deadline, described below) or "too slow" (after the deadline and prior to 1700 msec, the time at which feedback was presented) for speed-emphasis trials. If a response was not made within 1700 msec, the message "no press" was presented. The next trial began after an inter-trial interval of 1000 msec.

2.3. *Procedure*

The experiment began with three sets of practice blocks designed to familiarize participants with the speed and accuracy requirements of the task. Each set was composed of a series of short blocks of 16 trials that were repeated until the participant reached a criterion level of performance. The first practice set instructed participants to focus solely on the accuracy of their responses, ensuring that they could perceive the coherent motion in the display. The second practice set shifted the emphasis to response speed, using a series of sequentially faster response deadlines across the short blocks in the set. The second set was used to identify an appropriate response deadline on an individual basis to be used in the speed-emphasis condition of the main experiment. The final practice set randomized the two types of instructions from one trial to the next, mimicking the procedure used in the main experiment. Each trial began with a cue that instructed the participant to respond quickly or accurately. For full procedural details of the practice sets, see Supplementary Material.

The main experiment was identical to the mixed practice blocks except that each block consisted of 90 trials. Of these, 45 were cued for speed and 45 were cued for accuracy. Participants completed 6 experimental blocks, yielding a total data set of 540 trials per participant for the analyses reported below.

2.4. *Analysis*

The data from two of the seven control participants were excluded due to high error rates in the accuracy condition (>45%; chance = 50%). These participants reported that they were unable to see coherent motion in the stimulus display. The results presented below are therefore based on data from five patients and five control participants.

Conventional analyses of performance in speeded decision-making tasks analyze mean response time and accuracy with a focus on group comparisons of data averaged across individual participants. This form of analysis can be problematic in neuropsychological research when the number of participants in a patient sample is small as in the current study. Moreover, reducing each participant's data to a point estimate of response time and accuracy severely reduces the rich information available in individual data sets. Thus, we opted for a different approach that makes efficient use of the individual data sets and circumvents concerns with statistical power that may arise in small *n* studies.

To this end, we analyzed the behavioral data with a cognitive process model in a hierarchical Bayesian framework to quantify and compare response caution between patients and controls. Cognitive process models are quantitative analyses that decompose observed variables, such as choices and response times from all trials in our random dot motion task, into latent components of processing with deeper psychological interest, such as response caution and processing efficiency. The most successful class of cognitive process models of decision making in neuroscience and psychology are known as sequential sampling models (for overview, see Forstmann, Ratcliff, & Wagenmakers, 2016). Sequential sampling models assume that decisions are made through a gradual process of sampling noisy information from the stimulus environment. The sampled information is integrated into an evidence counter that tracks support for the response

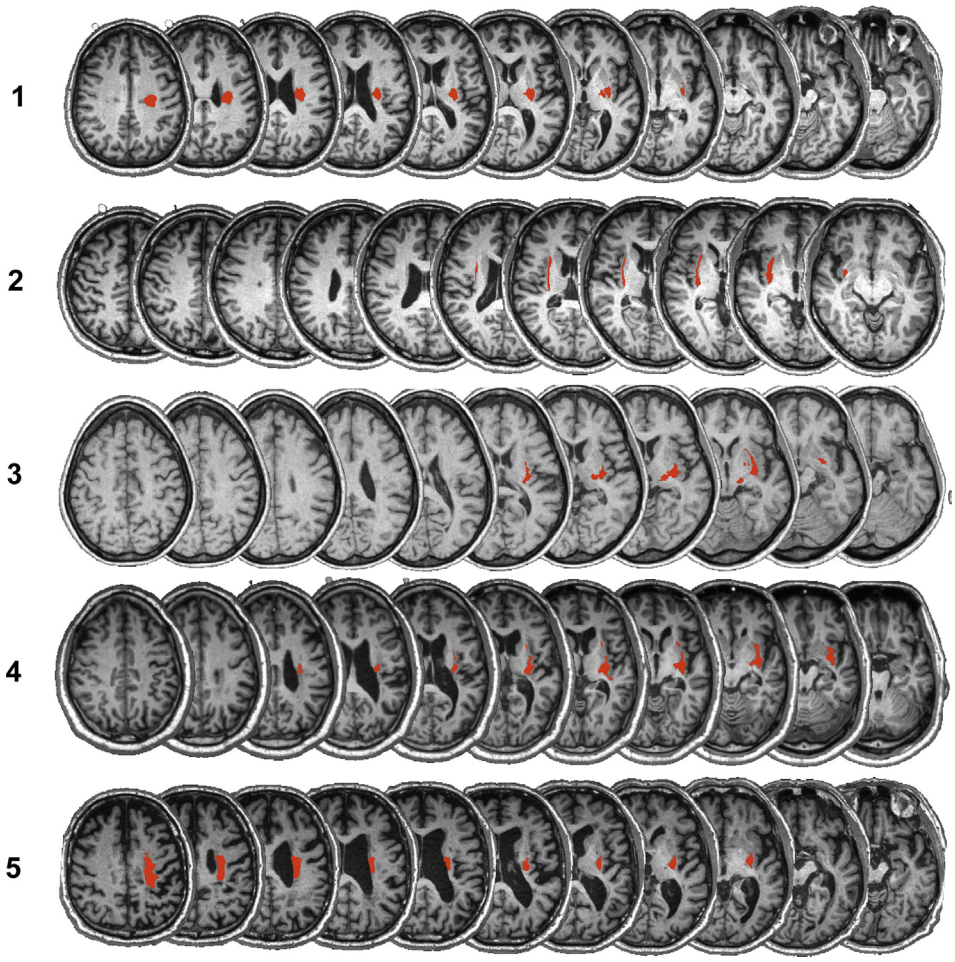

Fig. 1 – Lesion localization maps for the five patients. Maps are drawn on scale-adjusted individual anatomical images. The slices, from left to right, correspond to Z values from +40 to −10 in steps of 5 mm. Each slice is plotted with the left hemisphere to the right, and the right hemisphere to the left.

alternatives until the counter reaches a pre-determined threshold value, triggering a choice. Our analyses used a sequential sampling model known as the Linear Ballistic Accumulator (LBA; Brown & Heathcote, 2008, see Fig. 2B), but similar conclusions follow from other sequential sampling models (cf. Donkin, Brown, Heathcote, & Wagenmakers, 2011). In the main text we provide high-level details of the cognitive modeling analysis. For a complete explanation with full technical details see the Supplementary Material.

The LBA has two parameters of primary interest to the study hypotheses: the *drift rate* and the *response threshold*. The drift rate reflects the average speed at which information is extracted from the stimulus, an index of information processing efficiency. The LBA model represents the alternative response options (i.e., leftward motion, rightward motion in our task) in independent activation units. The response unit that matches the direction of stimulus motion (e.g., the unit coding for leftward motion when the stimulus moves to the left) will tend to have a larger drift rate than the competing response unit (the unit coding for rightward motion). These are commonly referred to as the correct drift rate and the error drift rate, respectively (see Fig. 2B). A scaled version of the difference between the correct and error drift rates gives a measure of sensitivity that is comparable to the d' sensitivity measure in the signal detection theory framework. Sensitivity is high – a large difference between the correct and error drift rates – in easy decision tasks, leading to both fast and correct decisions, on average. The converse also holds: sensitivity is low in difficult decisions, leading to slower responses with a larger probability of committing errors, on average.

The response threshold parameter indicates the amount of evidence required to commit to a response, and thus provides a measure of cautiousness. Response caution is often parameterized as a transformed version of the response threshold parameter, such as the distance between the response threshold and the average starting point of evidence accumulation. By changing the level of response caution, the LBA accounts for the SAT: for a given drift rate, high levels of response caution lead to slower responses with a low likelihood of errors, and low levels of response caution lead to faster responses with a greater likelihood of errors.

The choices and distributions of response times obtained from the random dot motion task were transformed into parameters of the LBA model (full details provided in Supplementary Material). We obtained separate measures of sensitivity and response caution for patients and controls in

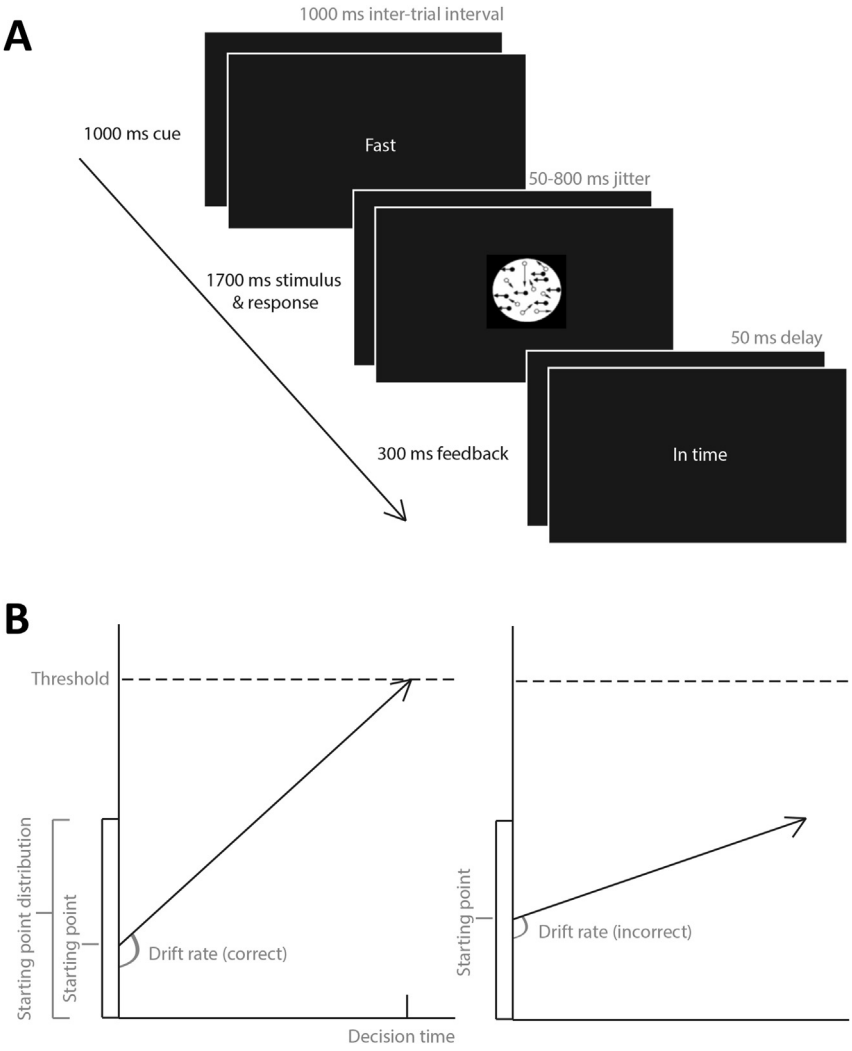

Fig. 2 – The speed-accuracy tradeoff task and the Linear Ballistic Accumulator (LBA) model. A) A sample trial from the random dot motion task. In this example, the participant was cued to make a fast decision, the stimulus moved to the left, and the participant responded within the specified time frame. B) Schematic representation of an LBA model race between two independent accumulators. The left accumulator corresponds to the correct alternative (with a higher drift rate), and the right accumulator corresponds to the incorrect alternative. The starting level of activation is randomly sampled from a uniform distribution, and information accumulation follows a linear rise toward a fixed threshold. A decision is made when one of the accumulators reaches threshold.

the speed- and accuracy-emphasis conditions. Our analyses were performed in a hierarchical Bayesian framework that provided estimates of the LBA parameters at the individual-participant and group levels (patients, controls). Our primary analyses focused on aggregate differences in the measure of sensitivity and response caution between patients and controls (i.e., group-level differences). This allowed us to test whether patients differed from controls in terms of response caution (i.e., the hypothesized effect of striatal lesions on SAT performance) or general sensitivity to perceptual information (possibly a more global effect of 'general brain damage'). We report the parameter effects in terms of odds, where larger odds indicate stronger evidence for an effect. Since we estimated the parameters in a Bayesian framework we do not report conventional *p*-values; however, one can interpret the reported odds as indicating positive evidence (>3:1), substantial evidence (>10:1), strong evidence (>30:1), or decisive evidence (>100:1) (cf. Jeffreys, 1961). The LBA has additional parameters that were estimated from data but since those parameters did not vary with respect to speed- or accuracy-emphasis instructions in our modeling, they do not arbitrate between the study hypotheses and are reported in Supplementary Material (Table S2).

3. Results and discussion

The LBA cognitive model provided a good account of the full distribution of response times for correct and error trials at the individual-participant and group levels (Fig. 3C; model predictions, shown as lines, closely align with data, shown as dots). Fig. 3C shows the expected pattern of results from a SAT manipulation: participants were faster when instructed to emphasize response speed (dots/lines shifted leftward along

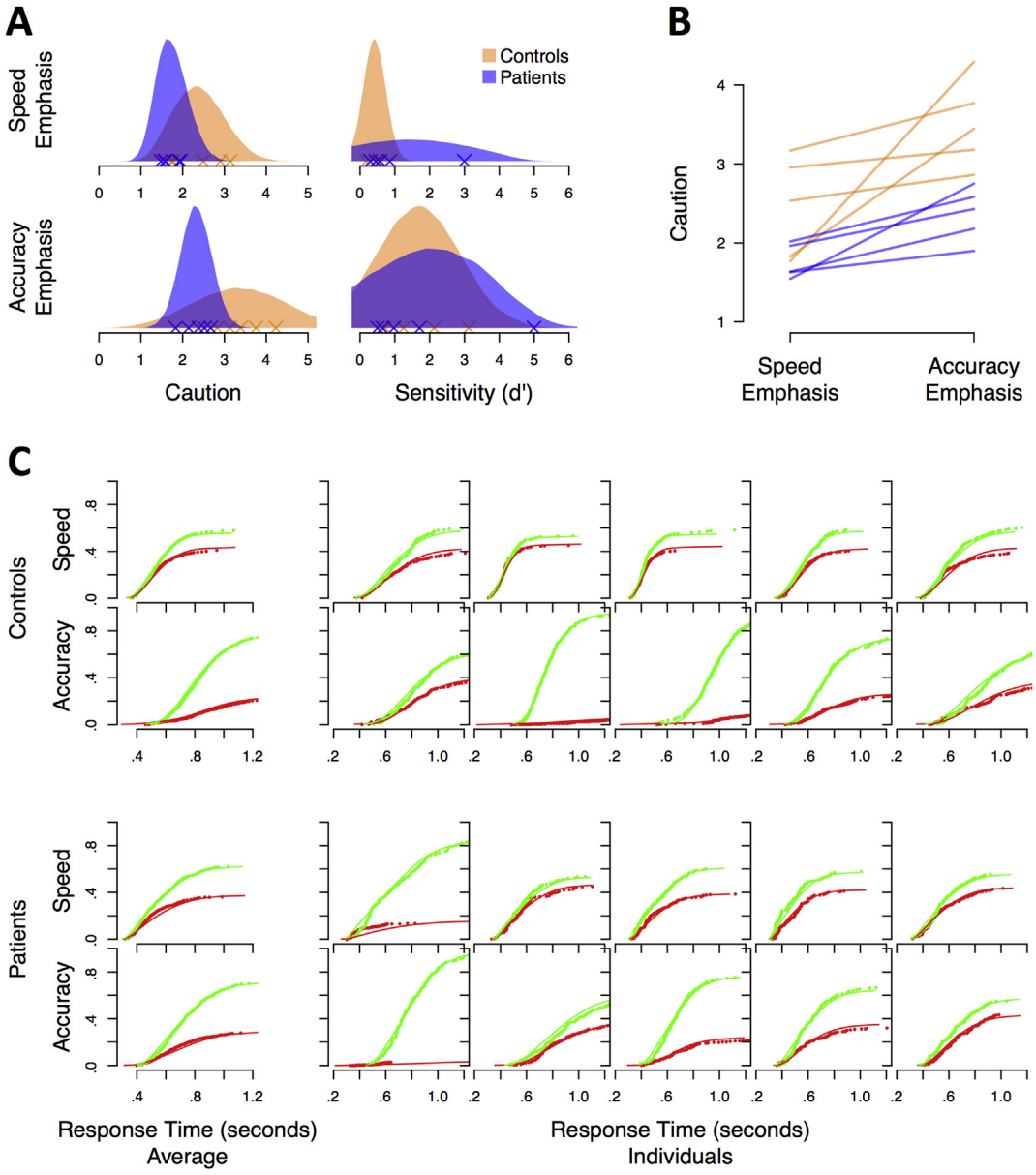

Fig. 3 – LBA model parameter estimates and goodness of fit to data. A) Posterior distributions of the caution (left column) and sensitivity (right column) measures predicted from the fit of the LBA model. The area under each curve sums to 1, and the height of the curve indicates the probability density. Marks on the *x*-axis correspond to the median of the individual participant posterior distributions. B) Changes in caution per individual, where each line represents a single participant's caution level in the speed- and accuracy-emphasis conditions, as estimated by the hierarchical Bayesian modeling. C) Cumulative distribution functions (CDFs) of the response time data. The dots indicate the observed data and lines indicate the posterior predictive distributions from the LBA model. The left column shows the data aggregated across participants, and the other five columns show the corresponding figures for individual participants. CDFs for correct responses are shown in green and incorrect responses in red, with the height of the distributions representing the proportion of correct and incorrect responses, respectively.

the *x*-axis for speed- *vs* accuracy-emphasis rows), and made fewer errors when instructed to emphasize response accuracy (red dots/lines are lower on the *y*-axis for accuracy- *vs* speed-emphasis rows). Taken together, this indicates that we can safely interpret the parameters of the model for our SAT manipulation. Table 2 shows the group-level differences in sensitivity and response caution.

Patients had marginally greater sensitivity to perceptual information than controls in the speed-emphasis condition, and near-identical sensitivity in the accuracy-emphasis condition. This result indicates that patients with striatal lesions were not impaired in their ability to process perceptual information, and thus did not differ to controls in terms of their general ability to perform the task.

Table 2 – Cognitive modeling results.

Parameter	Condition	Odds (X-to-1)	Patients	Controls
Sensitivity	Speed	3.9	**1.61**	.42
	Accuracy	1.0	**2.19**	1.72
Response caution	Speed	6.3	1.66	**2.31**
	Accuracy	21	2.32	**3.22**

Group-level effects for the LBA model measures of sensitivity and response caution, separately for the speed- and accuracy-emphasis conditions. Effects are expressed as the odds for the patient group having a larger value than the control group, or vice versa. The rightmost two columns present posterior mean parameter estimates for the two groups, with the higher value in boldface.

In contrast, there were clear differences between patients and controls in response caution, shown in Fig. 3A and B. Regardless of instruction condition, patients had reduced levels of response caution compared with controls; there was strong evidence for the effect when the accuracy of responding was emphasized (21-to-1 odds), with a more moderate effect when decision speed was emphasized (6.3-to-1 odds). These odds indicate that a difference between patients and controls was 21 and 6.3 times more likely than no difference between groups, respectively, for the accuracy- and speed-emphasis conditions. This result supports the hypothesized main effect that patients with focal lesions of the striatum have an impairment in establishing appropriate levels of caution in their decisions: for a given level of sensitivity, patients will respond sooner – on the basis of less information – than controls.

Moreover, there was positive evidence for an interaction between group and instruction condition on caution: controls showed a greater increase in response caution between the speed- and accuracy-emphasis conditions than patients (5.3-to-1 odds). Although this interaction effect was in the hypothesized direction – a smaller dynamic range in caution for patients than controls – the odds indicates relatively weak positive evidence. There is therefore only some evidence that controls exhibited greater flexibility than patients in adjusting their response threshold between the two types of instructions.

Our results show that activity in the human striatum during speeded perceptual decision-making is not merely a byproduct of some peripheral process associated with decision-making, but that the striatum may have a causal role in setting response caution. This hypothesis rests on the assumption that a unique set of structures supports a particular function (in this case, the striatum supports flexible adjustments to response caution). We recognize that alternative hypotheses are possible. For example, multiple structures and/or pathways may be essential for regulating response caution. Nonetheless, our results indicate that the integrity of the striatum is important for this process. More generally, these findings are consistent with theories of the basal ganglia as an action selector, with its activity regulating cortical action representations (Mink, 1996).

While all lesions affected the putamen, the lesions in our patient population were not sufficiently localized to indicate whether a specific subpart of the striatum is involved with adjusting response caution. Furthermore, implicating the striatum in adjusting response caution does not rule out involvement from other regions, either within the basal ganglia, such as the subthalamic nucleus (Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010), or in the prefrontal cortex, such as the pre-SMA (Forstmann et al., 2008) or the dorsolateral prefrontal cortex (Van Veen et al., 2008; Wenzlaff, Bauer, Maess, & Heekeren, 2011).

One slightly puzzling finding is that compared to instructions emphasizing response speed, patients only modestly increased their level of caution when instructed to emphasize accuracy. We anticipated the reverse scenario where patients would be unable to lower their level of caution when asked to respond quickly. This prediction was based on the assumption that, with reduced striatal inhibition of the basal ganglia output nuclei, there should be an increase in tonic inhibition of thalamo-cortical action representations (Mink, 1996). Nevertheless, our results reliably indicate impairments in setting response caution, where our cognitive modeling indicated a tendency towards impulsive behavior in patients, consistent with reports of increased impulsive behavior following striatal lesions in the rat (Eagle & Robbins, 2003). It may be that, with long-term absence of striatal disinhibition, the pallido-thalamo-cortical network adjusted its baseline activation levels, resulting in the more impulsive and less flexible behavioral pattern we observed here.

As with most neuropsychological studies, there are a few caveats to keep in mind. This study involved a small sample size. Analysis of small cohorts is commonplace in the human brain lesion literature, especially when the inclusion criteria are designed to select individuals with focal lesions limited to the region of interest (Ell, Marchant, & Ivry, 2006; Ell, Weinstein, & Ivry, 2010; Müller, Machado, & Knight, 2002; Roca et al., 2011; Shin, Aparicio, & Ivry, 2005; Van der Stigchel, Van Koningsbruggen, Nijboer, List, & Rafal, 2012). While the small sample size precludes analyses that map behavior–lesion relationships, they are crucial for addressing specific hypotheses about the role of a particular brain region for a particular behavior.

Our combination of cognitive modeling and Bayesian inference represents one way to address this practical limitation. Bayesian inference provides a rigorous method to analyze small sample sizes. This procedure reduces the risk of accepting the null hypothesis, providing a graded measure of the evidence for, and against, the null hypothesis. It also has the potential to identify situations in which the sample size is simply too small to draw any meaningful conclusions. In our Bayesian parameter estimation approach, differences observed in the posterior distributions of model parameters (cf. Fig. 3A) are driven entirely by effects in data, and the magnitude of those differences indicates the strength of evidence in favor of an effect or the absence of an effect (reflected in the odds we report). If our sample size were too small to provide sufficient information regarding our research hypotheses, we would not have observed differences between the posterior distributions of the model parameters between patients and controls. We confirmed this in a simulation study that verified the ability of our analysis approach to detect differences in key model parameters (full details provided in Supplementary Material).

3.1. *Conclusions*

Through cognitive modeling of behavioral data, we demonstrated that focal lesions of the human striatum impair the ability to strategically set an appropriate level of caution in a perceptual decision-making task, and that this result could not be attributed to a general inability to perform the task. These findings build upon previous neuroimaging studies that used correlational approaches to highlight a key role of the striatum in human decision-making, suggesting the striatum may have a causal role in setting response caution in decision-making. Our results are therefore consistent with models of the basal ganglia as an action selector.

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Supplementary material

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cortex.2016.09.023.

REFERENCES

Beck, A. T., Ward, C. H., Mendelson, M., Mock, J., & Erbaugh, J. (1961). An inventory for measuring depression. *Archives of General Psychiatry, 4*, 561–571.

Bogacz, R., Wagenmakers, E.-J., Forstmann, B. U., & Nieuwenhuis, S. (2010). The neural basis of the speed-accuracy tradeoff. *Trends in Neurosciences, 33*, 10–16.

Britten, K. H., Shadlen, M. N., Newsome, W. T., & Movshon, J. A. (1992). The analysis of visual motion: A comparison of neuronal and psychophysical performance. *The Journal of Neuroscience, 12*, 4745–4765.

Brown, S. D., & Heathcote, A. (2008). The simplest complete model of choice response time: Linear ballistic accumulation. *Cognitive Psychology, 57*, 153–178.

Ding, L., & Gold, J. I. (2012). Separate, causal roles of the caudate in saccadic choice and execution in a perceptual decision task. *Neuron, 75*, 865–874.

Donkin, C., Brown, S., Heathcote, A., & Wagenmakers, E.-J. (2011). Diffusion versus linear ballistic accumulation: Different models but the same conclusions about psychological processes? *Psychonomic Bulletin & Review, 18*, 61–69.

Eagle, D. M., & Robbins, T. W. (2003). Inhibitory control in rats performing a stop-signal reaction-time task: Effects of lesions of the medial striatum and d-amphetamine. *Behavioral Neuroscience, 117*, 1302–1317.

Ell, S. W., Marchant, N. L., & Ivry, R. B. (2006). Focal putamen lesions impair learning in rule-based, but not information-integration categorization tasks. *Cognition, 44*, 1737–1751.

Ell, S. W., Weinstein, A., & Ivry, R. B. (2010). Rule-based categorization deficits in focal basal ganglia lesion and Parkinson's disease patients. *Neuropsychologia, 48*, 2974–2986.

Forstmann, B. U., Anwander, A., Schäfer, A., Neumann, J., Brown, S., Wagenmakers, E.-J., et al. (2010). Cortico-striatal connections predict control over speed and accuracy in perceptual decision making. *Proceedings of the National Academy of Sciences of the United States of America, 107*, 15916–15920.

Forstmann, B. U., Dutilh, G., Brown, S., Neumann, J., von Cramon, D. Y., Ridderinkhof, K. R., et al. (2008). Striatum and pre-SMA facilitate decision-making under time pressure. *Proceedings of the National Academy of Sciences of the United States of America, 105*, 17538–17542.

Forstmann, B. U., Ratcliff, R., & Wagenmakers, E.-J. (2016). Sequential sampling models in cognitive neuroscience: Advantages, applications, and extensions. *Annual Review of Psychology, 67*, 641–666.

Ivanoff, J., Branning, P., & Marois, R. (2008). fMRI evidence for a dual process account of the speed-accuracy tradeoff in decision-making. *PLoS One, 3*. http://dx.doi.org/10.1371/journal.pone.0002635.

Jeffreys, H. (1961). *Theory of probability* (3rd ed.). New York, NY: Oxford University Press.

Jenkinson, M., Bannister, P., Brady, M., & Smith, S. (2002). Improved optimization for the robust and accurate linear registration and motion correction of brain images. *NeuroImage, 17*, 825–841.

Jenkinson, M., & Smith, S. (2001). A global optimisation method for robust affine registration of brain images. *Medical Image Analysis, 5*, 143–156.

Lo, C., & Wang, X. (2006). Cortico–basal ganglia circuit mechanism for a decision threshold in reaction time tasks. *Nature Neuroscience, 9*, 956–963.

Mink, J. W. (1996). The basal ganglia: Focused selection and inhibition of competing motor programs. *Progress in Neurobiology, 50*, 381–525.

Müller, N. G., Machado, L., & Knight, R. T. (2002). Contributions of subregions of the prefrontal cortex to working memory: Evidence from brain lesions in humans. *Journal of Cognitive Neuroscience, 14*, 673–686.

Niv, Y., Daw, N. D., & Joel, D. (2007). Tonic dopamine: Opportunity costs and the control of response vigor. *Psychopharmacology, 191*, 507–520.

Pachella, R. G. (1974). The interpretation of reaction time in information-processing research. In B. H. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition* (pp. 41–82). Hillsdale, NJ: Lawrence Erlbaum.

Reed, A. V. (1973). Speed-accuracy trade-off in recognition memory. *Science, 181*, 574–576.

Robbins, T. W., & Everitt, B. J. (2007). A role for mesencephalic dopamine in activation: Commentary on Berridge (2006). *Psychopharmacology, 191*, 433–437.

Roca, M., Torralva, T., Gleichgerrcht, E., Woolgar, A., Thompson, R., Duncan, J., et al. (2011). The role of area 10 (BA10) in human multitasking and in social cognition: A lesion study. *Neuropsychologia, 49*, 3525–3531.

Shin, J. C., Aparicio, P., & Ivry, R. B. (2005). Multidimensional sequence learning in patients with focal basal ganglia lesions. *Brain and Cognition, 58*, 75–83.

Spreen, O., & Strauss, E. (1998). *A compendium of neuropsychological tests: Administration, norms and commentary*. New York, NY: Oxford University Press.

Van der Stigchel, S., Van Koningsbruggen, M., Nijboer, T. C. W., List, A., & Rafal, R. D. (2012). The role of the frontal eye fields in the oculomotor inhibition of reflexive saccades: Evidence from lesion patients. *Neuropsychologia, 50*, 198–203.

Van Maanen, L., Brown, S. D., Eichele, T., Wagenmakers, E.-J., Ho, T., Serences, J., et al. (2011). Neural correlates of trial-to-trial fluctuations in response caution. *The Journal of Neuroscience, 31*, 17488–17495.

Van Veen, V., Krug, M. K., & Carter, C. S. (2008). The neural and computational basis of controlled speed-accuracy tradeoff during task performance. *Journal of Cognitive Neuroscience, 20*, 1952–1965.

Wechsler, D. (2008). *Wechsler adult intelligence scale – Fourth edition*. San Antonio, TX: Pearson.

Wenzlaff, H., Bauer, M., Maess, B., & Heekeren, H. R. (2011). Neural characterization of the speed-accuracy tradeoff in a perceptual decision-making task. *The Journal of Neuroscience, 31*, 1254–1266.

Wickelgren, W. A. (1977). Speed-accuracy tradeoff and information processing dynamics. *Acta Psychologica, 41*, 67–85.

Winkel, J., Van Maanen, L., Ratcliff, R., Van der Schaaf, M. E., Van Schouwenburg, M. R., Cools, R., et al. (2012). Bromocriptine does not alter speed–accuracy tradeoff. *Frontiers in Decision Neuroscience, 6*, 126. http://dx.doi.org/10.3389/fnins.2012.00126.