

Regional specialization within the human striatum for diverse psychological functions

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Decades of animal and human neuroimaging research have identified distinct, but overlapping, striatal zones, which are interconnected with separable corticostriatal circuits, and are crucial for the organization of functional systems. Despite continuous efforts to subdivide the human striatum based on anatomical and resting-state functional connectivity, characterizing the different psychological processes related to each zone remains a work in progress. Using an unbiased, data-driven approach, we analyzed large-scale coactivation data from 5,809 human imaging studies. We (i) identified five distinct striatal zones that exhibited discrete patterns of coactivation with cortical brain regions across distinct psychological processes and (ii) identified the different psychological processes associated with each zone. We found that the reported pattern of cortical activation reliably predicted which striatal zone was most strongly activated. Critically, activation in each functional zone could be associated with distinct psychological processes directly, rather than inferred indirectly from psychological functions attributed to associated cortices. Consistent with well-established findings, we found an association of the ventral striatum (VS) with reward processing. Confirming less well-established findings, the VS and adjacent anterior caudate were associated with evaluating the value of rewards and actions, respectively. Furthermore, our results confirmed a sometimes overlooked specialization of the posterior caudate nucleus for executive functions, often considered the exclusive domain of frontoparietal cortical circuits. Our findings provide a precise functional map of regional specialization within the human striatum, both in terms of the differential cortical regions and psychological functions associated with each striatal zone.

human striatum | parcellation | corticostriatal circuits | coactivation analysis | NeuroSynth

In addition to its central role in selecting, planning, and executing motor behavior (1, 2), the human striatum has been reported to be involved in diverse psychological functions, including emotion generation and regulation (3, 4), reward-related processes and decision making (5, 6), and executive functions (7, 8). These discrete functions are thought to map onto distinct functional striatal zones, which participate in separable basal ganglia-thalamocortical circuits (9–12) and are critical for the organization of behavior.

Following this logic, recent attempts to parcellate the human striatum using diffusion tensor imaging (DTI) (13, 14) and resting-state functional connectivity (RSFC) (15–17) have relied on patterns of corticostriatal connectivity to identify striatal zones. Although very useful, these studies have been limited to inferring striatal function indirectly via psychological functions of connected cortical regions. In addition, it remains unclear how anatomical connections and RSFC map onto different psychological processes (18). Finally, RSFC is sometimes epiphenomenal (19), and fiber tract reconstruction with DTI is inaccurate for complex axonal projections underlying frontal corticostriatal connectivity (17).

A separate body of work has attempted to differentiate striatal contributions directly to behavior empirically. However, these empirical investigations have focused on a restricted set of paradigms that may fail to capture the full range of striatal function, especially in humans. For example, converging evidence suggests a division of labor between the ventral striatum (VS) and dorsal striatum for Pavlovian and instrumental conditioning, respectively (20, 21). Within

the dorsal striatum, medial regions support behavioral flexibility and lateral regions support well-learned behavior (22, 23). This work has greatly advanced our understanding of the similarities of striatal function in human and nonhuman animals. However, because of this strong reliance on classic learning paradigms, the integration of ideas about how the striatum is involved in uniquely human psychological functions, such as working memory, planning, and language, remains a work in progress.

To generate a comprehensive and precise functional map of the human striatum, in terms of associations with both cortical brain regions and psychological tasks, we simultaneously analyzed corticostriatal coactivation patterns and the frequency of psychological terms in the full text of 5,809 neuroimaging studies (24). In contrast to studies of RSFC, we defined corticostriatal associations based on coactivation in task-related responses across studies. A cortical voxel and a striatal voxel were coactivated if a study reported activation in both voxels. This metric groups voxels that are associated with similar psychological processes. Similar to RSFC, this metric does not imply direct functional coupling of coactivated voxels. In contrast to existing work, we attempted to associate psychological functions with striatal areas directly, rather than inferring them indirectly based on the psychological functions of connected cortical areas. Sampling across a broad spectrum of neuroimaging studies, without regard for the psychological process under investigation, allowed a large-scale comparison of associations of striatal subregions with diverse psychological processes. This data-driven approach allowed us to (i) localize five striatal zones based on their coactivation with cortical brain areas and (ii) simultaneously characterize the association of each zone with psychological states in a relatively unbiased manner, including potential associations overlooked in both individual hypothesis-driven studies and studies of RSFC.

Significance

The subcortical striatum is critical for the planning and execution of motor behavior, and its dysfunction is associated with disorders such as Parkinson's disease. More recently, the human striatum has also been reported to be involved in heterogeneous nonmotor psychological functions. However, detailed functional mappings of human psychological processes to striatal regions have been bound by theoretical and methodological limitations, including a strong focus on experimental paradigms derived from animal research, and the tendency to infer function from anatomical connectivity, rather than task-related activation. To overcome these limitations, we used a large-scale, unbiased, data-driven approach, and generated a precise, comprehensive functional map, directly associating striatal zones with the broadest range of psychological processes to date.

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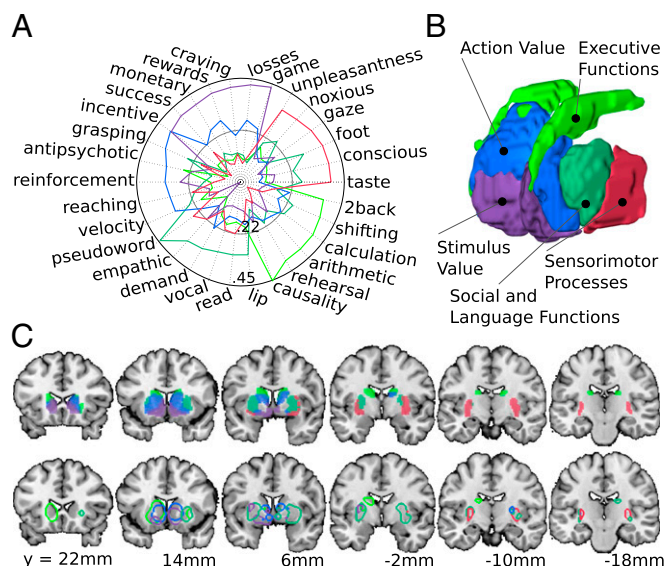


Fig. 3. To identify the psychological functions associated with each striatal zone, we calculated for each psychological term included in the NeuroSynth database its likelihood ratio of appearing in a study, given that activation was reported anywhere within a zone. (A) Distribution of likelihood ratios across functional zones indicates a clear functional dissociation. (B) Subjective summary of the main psychological function of each functional zone in a working model. (C) Based on the reported striatal activation and the occurrence of psychological terms in each study, it was possible to identify the most representative studies for each functional zone. The striatal zones identified in our coactivation analysis (Top) and a reconstructed outline of the activation reported in the representative studies (Bottom) are shown.

actions, contrasting with the above role of the VS in evaluating the value of stimuli (35, 36).

Pp: Sensorimotor Processes. The Pp was associated with psychological terms such as “foot,” “noxious,” and “taste.” The most representative study reported activation of this region in response to painful stimulation at the back of the left hand and foot of participants (37). Anatomically, the most reliable and specific coactivation is with sensorimotor cortices, and the posterior and midinsula and operculum (secondary somatosensory cortex SII) in particular, some parts of which are specifically associated with pain (38). Together, these findings suggest a broad involvement of this area in sensorimotor functions, including aspects of their affective qualities.

Pa: Social- and Language-Related Functions. The adjacent Pa was associated with psychological terms such as “read,” “vocal,” and “empathic,” and it is coactivated with frontal areas anterior to the ones coactivated with the Pp, demonstrating topography in frontostriatal associations. These anterior regions have been implicated in language processes (39, 40). The most representative study (41) partially supports a role of this area in social- and language-related functions; it reported a stronger activation of the Pa in experienced singers, but not when novices were singing.

Cp Nucleus: Executive Functions. This area was originally considered a part of the oculomotor circuit (11). In line with recent observations (42), we found that the Cp is associated with psychological terms such as “causality,” “rehearsal,” and “arithmetic.” The representative study (43) reported this region to be part of a network that included dorsolateral PFC and ACC, which supported inhibitory control and task set-shifting. These results suggest a broad, and previously underappreciated, role for the Cp in cognitive control.

Discussion

We analyzed task-dependent changes in corticostriatal coactivation patterns across 5,809 studies to identify different

functional zones within the striatum, and to decode the psychological function of these striatal zones simultaneously. Although we found evidence for a continuum-based organization of the striatum, we nevertheless were able to identify distinctive properties associated with five different striatal zones, with each making different contributions to human cognition and behavior. Our results expand on the results of previous studies, which delineated striatal regions based on anatomical criteria in animals (11) and on RSFC (17) and DTI (13–15) in humans. In relation to this previous work, we found that it was possible to (i) define striatal subregions based on a large sample of task-related neuroimaging data, (ii) predict striatal activation accurately based on patterns of cortical activation, and (iii) identify unique associations between regional striatal activation and both cortical networks and task types.

Some of the identified associations are now well established, such as the association between VS activation and reward. However, because we followed an unbiased, data-driven approach, we also identified associations between striatal activation and other psychological functions that have often been considered to be primarily cortical. In particular, cognitive functions, such as working memory and arithmetic, were associated with activation in the Cp, and social functions, such as language and empathy, were associated with activation of the Pa. Different aspects of affective function were associated with distinct zones, including stimulus-driven value associated with reinforcers such as money (VS), action-outcome value (Ca), social value (Pa), and somatosensory pain and pleasure (Pp).

Among the five striatal zones, we identified a VS cluster that contained the nucleus accumbens and ventral aspects of the Pa and Ca nucleus. This region was characterized by a strong coactivation with OFC and ventromedial PFC. This VS-OFC network was previously difficult to identify in humans through DTI, because of the diffuse nature of axonal projections between the two areas (17). The results of our decoding procedure for this functional zone are consistent with its well-established role in processing primary rewards, such as food, but also abstract rewards, such as money, as demonstrated by several recent human decision-making studies (34, 44).

Consistent with previous findings (28), we found that the Pa and Pp were topographically connected with different sensorimotor cortical areas. The two zones also differed functionally. Our term-based analysis suggests that the Pa is involved in language and other social functions, such as empathy. At the same time, the cortical coactivation maps suggest a strong association with Broca’s area, which enables language production. In contrast to the Pa, we found that the Pp was associated with sensorimotor processes. Interestingly, we found that the most representative study for this region (37), according to our analysis, used painful stimulation of hands and feet. Previous studies of pain have identified a network of pain-associated somatosensory and perilimbic regions (e.g., medial thalamus, anterior insula, dACC) (45), but have seldom discussed the Pp as part of this circuit. Nonetheless, consistent with our findings here, this region was also identified to be preferentially activated during aversive conditions, compared with more anterior VS activation for appetitive conditions (46).

The results of our decoding procedure extend and refine a growing body of evidence for dissociation between the Ca and Cp (7, 8, 42, 43). This evidence suggests that the Ca is involved in a diverse set of functions supporting action evaluation and incentive behavior, whereas the Cp supports executive functions. These results contrast with taxonomies based on nonhuman primate data (11), which locate the body of the caudate within an oculomotor circuit. They also diverge from the conclusions of a recent human metaanalysis (47), which associated the caudate head with cognition and emotion and the caudate body with perception and action. We also found further evidence for a previously underdiscussed dissociation between VS and Ca, such that the VS may be involved in representing available rewards and the Ca in representing the expected outcome of different actions (5, 6).

Existing neural network models of corticostriatal interactions offer a mechanistic account of how the Cp may support executive functions (48). They postulate that the striatum modulates the destabilization of persistent patterns of activation in cortical areas, thus controlling

working memory updating, manipulation of items in working memory, and how cortical working memory circuits influence downstream areas. Future analyses may reveal further regional specialization within the caudate nucleus for different aspects of executive functions, given recent findings suggesting that common executive function tasks are overlearned and activate posterior parts of the PFC most closely associated with proximal action selection (49, 50), rather than anterior PFC circuits associated with goal formation and selection (51, 52).

Despite the fact that psychological functions of different striatal zones in the present study were identified solely based on striatal activation, rather than on cortical activation, the results may indirectly inform our understanding of the psychological functions of associated cortical areas. For example, the Ca showed a stronger coactivation with the right PFC and an involvement in incentive behavior, whereas the Cp showed a stronger coactivation with the left PFC and an involvement in executive functions. At the same time, we found that the left and right hemispheres of the Cp were only weakly correlated. This difference between the Ca and Cp nucleus represents an exception to the previously reported tendency of striatal areas to be interconnected to ipsilateral cortical areas (29). Furthermore, whereas the role of left dorsolateral PFC in executive function is well established, the role of right PFC is slightly less clear. Our analysis of striatal function suggests that this region may be involved in nonverbal executive functions in the support of incentive behavior (53–56).

To understand why our metaanalytic results only partially overlap with existing RSFC parcellations of the striatum, one has to appreciate the difference between the two approaches. In the present study, coactivation of two voxels indicates that a study reported significant task-related BOLD responses in both voxels in the same set of studies; that is, both voxels were correlated with experimental variables investigated in a study, but were not necessarily correlated with each other within an experimental session. Furthermore, although much has been made of similarities between task and resting-state data (57), resting-state data only represent a subset of tasks related to rest, with large contributions from (i) ongoing maintenance-related activation that is apparent even under anesthesia and (ii) spontaneous cognition, including mind-wandering and episodic retrieval/projection (18). Functional striatal zones can only then be dissociated if the tasks and psychological states included in the dataset differ in how they simultaneously modulate activation in striatal and cortical voxels. Thus, the divergence of our parcellation from RSFC parcellations may be explained by the fact that the NeuroSynth database includes studies using a wide array of different psychological tasks (58), and because it is based on coactivation rather than RSFC. Nevertheless, this divergence also suggests that even though the results of our cluster analysis were highly robust, different striatal zones may have emerged had we performed it on a measure other than coactivation. Interestingly (59), found that patterns of striatal dopamine release did not converge with structural subdivisions, but with corticostriatal activation patterns, which were also the basis of our parcellation (SI Appendix, Fig. S12 shows results based on the NeuroSynth database).

In summary, following a relatively unbiased, data-driven meta-analytic approach analyzing coactivation of striatal and cortical areas in 5,809 studies, we were able to create a link between existing data on the anatomical and physiological characteristics of striatal regions and psychological functions. Because we did not limit our metaanalysis to studies that specifically targeted striatal function, our results extend previous knowledge of the involvement of the striatum in reward-related decision-making tasks, and provide a detailed functional map of regional specialization for diverse psychological functions, some of which are sometimes thought of as being the exclusive domain of the PFC.

Materials and Methods

Metaanalytic Coactivation Analysis. We relied on the NeuroSynth database to gain a comprehensive and unbiased window into coactivation of the striatum with other regions. The NeuroSynth database contains activation coordinates for 5,809 functional MRI (fMRI) studies that were not selected for specific criteria, or with regard to the psychological processes under investigation, but only for the presence of reported brain activations; hence, it is highly representative of the broader neuroimaging field (26). In this database, 10-mm boxcar smoothing was applied to activation coordinates to increase the robustness against differences in smoothing kernels across studies. We used *k*-means clustering to identify functional striatal zones, based on whether they showed similar corticostriatal coactivation patterns across studies. Details are provided in SI Appendix.

Naive Bayes Classifier. The classifier estimated for each functional striatal zone the posterior probability of it being the most active one in a study, given the pattern of cortical activation reported in a study. We used a bootstrapping approach to establish confidence intervals for whether a cortical voxel is more strongly associated with a particular striatal zone than with any other striatal zone. Details are provided in SI Appendix.

Comparison with the Results of Haber and Knutson. To compare our parcellation with the results of Haber and Knutson (26), we evaluated, for each striatal voxel, with which frontal cortical region of interest (ROI) of this previous work it exerted the strongest correlation across studies. For this purpose, we calculated for each study the proportion of active voxels within each ROI. In contrast to the analyses above, which depended on complex global patterns of cortical activation, we only considered positive correlations in this comparison, because Haber and Knutson (26) investigated direct corticostriatal projections with local injections of anterograde tracers in cortex. Convergent input from a cortical region is often thought to have an excitatory effect on striatal neurons (60). Correlations of each frontal ROI were Z-scored across striatal zones, because of all frontal ROIs, the dACC demonstrated the strongest correlation with a large majority of striatal voxels (SI Appendix, Fig. S7). ROIs were defined according to the automated anatomical labeling (AAL) atlas (61).

Term-Based Analysis. To identify the psychological functions associated with each striatal zone, we calculated the likelihood ratio *LR* that a psychological term occurred in the full text of a study ($T+$), given that activation was reported anywhere within the striatal zone (BG_k+): $LR = Pr(T+|BG_k+)/Pr(T-|BG_k+)$. For each functional zone, we report the six terms with the highest likelihood ratio and the likelihood ratio for this term for the other zones, yielding a total of 30 psychological terms. By reporting the likelihood ratio as defined above, the results are intentionally biased toward also identifying terms that only appeared in very few of the studies included in the database. This analysis was performed over a core set of 525 psychologically relevant terms included in the NeuroSynth dataset. These terms were not specifically chosen for the present metaanalysis, but were determined in a previously published study (24). The terms were not associated with any specific fMRI activity, but only with the article as a whole.

Representative Studies. We defined the representativeness of a study for striatal zone *k* as the product of how selectively the study reported activation in this zone, and the sum of the frequencies at which the psychological terms associated with the functional zone occurred in a study. Specifically, we divided the sum of activated voxels within each functional zone by the sum of total activated striatal voxels: $A_k = \sum_n a_n \delta_{nk} / \sum_n a_n$, where $\delta_{nk} = 1$ if voxel *n* is in zone *k* and $\delta_{nk} = 0$ otherwise. The sum T_k of the word frequencies of the psychological terms associated with a functional zone was calculated as $T_k = \sum_m t_{mk}$, where t_{mk} is the frequency of term *m*, associated with zone *k*. The study with the highest product $A_k T_k$ was selected as the most representative one for zone *k*.

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