



Arkypallidal neurons in the external globus pallidus can mediate inhibitory control by altering competition in the striatum

Cristina Giossi^{a,b}, Jyotika Bahuguna^c, Jonathan E. Rubin^{d,e}, Timothy Verstynen^{e,f,1,2}, and Catalina Vich^{a,b,1,2}

Edited by Terrence Sejnowski, Salk Institute for Biological Studies, La Jolla, CA; received May 7, 2024; accepted October 3, 2024

Reactive inhibitory control is crucial for survival. Traditionally, this control in mammals was attributed solely to the hyperdirect pathway, with cortical control signals flowing unidirectionally from the subthalamic nucleus (STN) to basal ganglia output regions. Yet recent findings have put this model into question, suggesting that the STN is assisted in stopping actions through ascending control signals to the striatum mediated by the external globus pallidus (GPe). Here, we investigate this suggestion by harnessing a biologically constrained spiking model of the cortico-basal ganglia-thalamic (CBGT) circuit that includes pallidostriatal pathways originating from arkypallidal neurons. Through a series of experiments probing the interaction between three critical inhibitory nodes (the STN, arkypallidal cells, and indirect pathway spiny projection neurons), we find that the GPe acts as a critical mediator of both ascending and descending inhibitory signals in the CBGT circuit. In particular, pallidostriatal pathways regulate this process by weakening the direct pathway dominance of the evidence accumulation process driving decisions, which increases the relative suppressive influence of the indirect pathway on basal ganglia output. These findings delineate how pallidostriatal pathways can facilitate action cancellation by managing the bidirectional flow of information within CBGT circuits.

reactive inhibitory control | stop-signal task | information flow | decision-making | basal ganglia

Imagine standing at the top of a ski slope, poised to descend. Just as you are about to start, something captures your attention in your periphery, prompting you to suddenly halt. A fearless skier then shoots past you, narrowly avoiding a collision. This scenario highlights how the fast suppression of a planned action in response to an external stimulus, known as reactive inhibition (1), can be crucial for survival.

The classical model of reactive inhibition posits that action cancellation solely depends on the hyperdirect pathway, which directly drives inhibition of the thalamus by ramping up inhibitory signals from the internal globus pallidus (GPi) via activation of the subthalamic nucleus (STN) (2). According to this framework, the hyperdirect pathway acts as a brake, facilitating the immediate termination of upcoming actions (3, 4). However, the dynamics of STN firing elicited by an external stop cue is largely inconsistent with this classical model, exhibiting a fast and brief burst that precedes, but is not coincidental with, basal ganglia output signals that drive suppression of the thalamus (5). Alternatively, recent research has highlighted the involvement of a previously underappreciated cell type within the external globus pallidus (GPe), the arkypallidal neurons (Arky), that appear to be crucial for external stop cues to induce termination of a planned action (5–8). These neurons, characterized by their ascending GABAergic projections to the striatum, target both spiny projection neurons (SPNs, split into direct, dSPNs, and indirect, iSPNs, pathway neurons) and fast-spiking interneurons (FSIs) (9, 10), making the pallidostriatal pathways potential drivers of reactive inhibition by recruiting striatal systems into the cancellation process (11–15).

While it is now clear that pallidostriatal pathways play a role in the inhibition of planned actions, the mechanics of their influence remain unclear. To understand this, we employed a biologically constrained spiking neural network model of cortico-basal ganglia-thalamic (CBGT) circuits, integrating recent empirical findings on the pallidostriatal pathways and simulating behavior in the stop signal task. We first replicated experimental findings on action inhibition by delivering a stop signal, separately, to each of three critical cell populations within the CBGT network (STN, Arky, or iSPN), which we implemented by up-regulating the firing frequency of each target population. We then explored the causal role that pallidostriatal pathways play in reactive inhibition by suppressing arkypallidal activity or modifying the efficacy of pallidostriatal connections to SPNs during additional simulations. Our analysis elucidates how the GPe can modulate

Significance

Recent research highlights the crucial role of pallidostriatal pathways in action inhibition, although the details of this process are not fully understood. By modeling the cortico-basal ganglia-thalamic (CBGT) circuitry, including recently explored inhibitory projections from arkypallidal cells to the striatum, in a simulation of a stop signal task, we show how these pathways facilitate inhibitory information flow in CBGT circuits by adjusting the balance between direct and indirect pathways during decision-making. These findings offer broad perspectives on the mechanics of action inhibition and suggest future experimental directions.

Author affiliations: ^aDepartament de Ciències Matemàtiques i Informàtica, Universitat de les Illes Balears, Palma 07122, Spain; ^bInstitute of Applied Computing and Community Code, Palma 07122, Spain; ^cLaboratoire de Neurosciences Cognitives et Adaptatives, Université de Strasbourg, Strasbourg 67000, France; ^dDepartment of Mathematics, University of Pittsburgh, Pittsburgh, PA 15213; ^eCenter for the Neural Basis of Cognition, Pittsburgh, PA 15213; and ^fDepartment of Psychology and Neuroscience Institute, Carnegie Mellon University, Pittsburgh, PA 15213

Author contributions: C.G., J.B., J.E.R., T.V., and C.V. designed research; C.G. and J.B. performed research; C.G., J.B., J.E.R., T.V., and C.V. analyzed data; and C.G., J.B., J.E.R., T.V., and C.V. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

Copyright © 2024 the Author(s). Published by PNAS. This article is distributed under [Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 \(CC BY-NC-ND\)](https://creativecommons.org/licenses/by-nc-nd/4.0/).

¹T.V. and C.V. contributed equally to this work.

²To whom correspondence may be addressed. Email: timothyv@andrew.cmu.edu or catalina.vich@uib.es.

This article contains supporting information online at <https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2408505121/-/DCSupplemental>.

Published November 13, 2024.

the competition between the direct and indirect striatal pathways that mediates evidence accumulation during decision-making (16–18).

Results

Simulating Reactive Inhibition. We used our computational model of the CBGT network to simulate a normative version of the well-studied stop-signal task (Fig. 1*A*) (19–21). Each trial begins with the presentation of an imperative stimulus (the *Go* cue), that drives cortical projections targeting the striatal SPNs. The trial decision phase reflects the entire evidence accumulation window, where iSPNs and dSPNs in the striatum compete to control the signals generated by the thalamic region targeted by basal ganglia output (16–18). When the thalamic firing rate reaches a threshold (30 Hz), an action is triggered, and the time between the imperative stimulus and the action onset is recorded as the reaction time (RT). Note that our RT measure lacks the movement time component of traditional RTs recorded experimentally. At 70 ms after the imperative stimulus onset, we present the stop signal (see *Materials and Methods*, Stop signal task). This signal boosts the activity of the targeted cells, which reduces the likelihood that the thalamic activity will reach the action threshold. The timing and amplitude of the stop signal were determined empirically based on the network’s stopping probability (*SI Appendix*, Figs. S1–S3) and reflect the condensed timeline of our simulated decision process relative to experiments in which sensory and motor processes prolong the overall chain

of events. An action is considered to be successfully stopped if the thalamic threshold is not reached within the trial window (300 ms) and therefore no action is registered.

For this study, we injected the stop signal into one of three CBGT cell populations that have been experimentally shown to inhibit behavior: iSPNs (22), STN (4), and Arky (5, 6) (Fig. 1*B*). The iSPNs are the primary input of the indirect pathway and are traditionally considered to drive proactive inhibitory control by suppressing the thalamus as part of the direct/indirect pathway competition (16, 23, 24). The STN cells, on the other hand, reflect the primary basal ganglia input from the cortical hyperdirect pathway (2). This circuit bypasses the striatum altogether and is thought to provide a fast control mechanism for action suppression (3). Finally, the recently rediscovered Arky cells (25) provide inhibitory projections to striatal iSPNs, dSPNs, and FSIs (6, 7, 9, 10, 26–31). Importantly, activation of Arky cells has recently been shown to suppress actions (5, 6, 8).

Activation of these target populations individually achieved varying degrees of action suppression ($F[7,29] = 113.16$, $P < 0.0001$; Fig. 1*C*). Stimulating the STN alone had the weakest influence on stopping, with an 11% stopping probability that improved only marginally over the 4% chance “stopping” probability during trials when no stop signal was delivered. These probabilities were far lower than the stopping probabilities that we observed with Arky-only (41%) and iSPN-only (71%) stimulation. We next considered the stimulation of pairs of regions, with the best performance, a 69% stopping probability, occurring with simultaneous STN and iSPN stimulation, comparable to

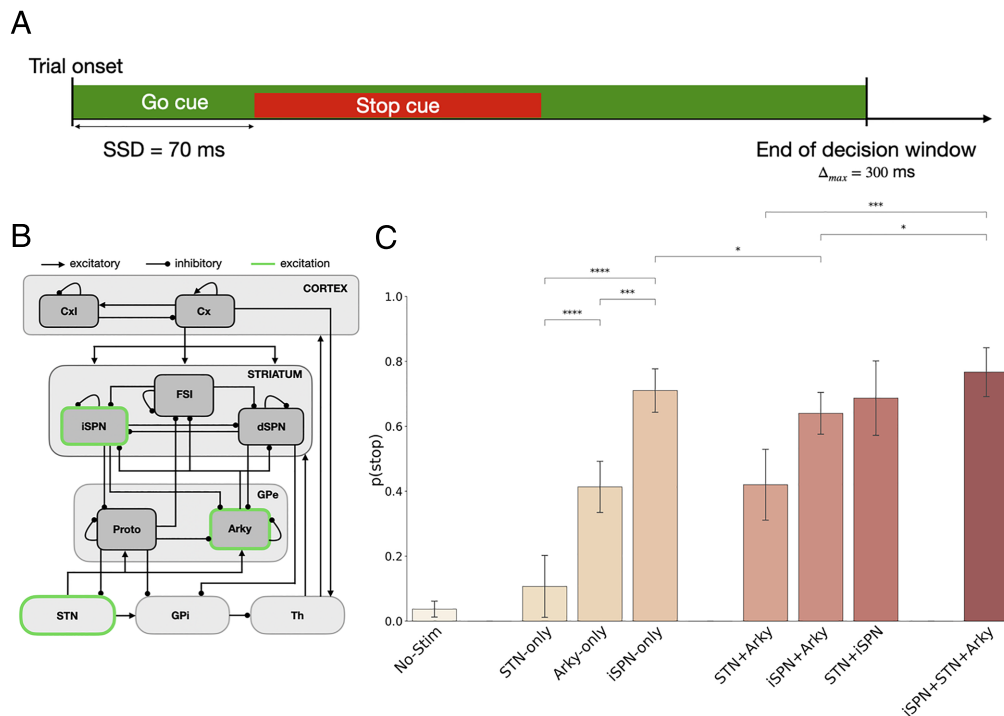


Fig. 1. Simulating reactive inhibition. (A) Schematics of our computational implementation of the stop signal task paradigm. The trial onset corresponds to the presentation of a primary stimulus (the “Go” cue, in green), which is sustained until the end of the decision window. A secondary stop stimulus follows (“Stop” cue, in red), instructing the network agent to withhold the action selection process. The delay between the onsets of the two stimuli is referred to as stop signal delay (SSD; 70 ms). The maximum duration of the decision phase corresponds to $\Delta_{max} = 300$ ms. (B) CBGT network architecture. Arrows depict excitatory projections while circles represent inhibitory connections. Green outlined nuclei indicate the populations that were externally stimulated to simulate the effects of the stop signal presentation. Cx: cortex; CxI: cortical interneurons; FSI: fast-spiking interneurons; iSPN: indirect pathway spiny projection neurons; dSPN: direct pathway spiny projection neurons; GPe: external globus pallidus; Proto: GPe prototypical neurons; Arky: GPe arkypallidal neurons; STN: subthalamic nucleus; GPI: internal globus pallidus; Th: thalamus. (C) Stopping probability across different stimulation cases. Individually, iSPN stimulation produces a ~71% of chance of stopping, Arky ~41%, and STN ~11%. The simultaneous stimulation of all three nuclei produces an overall greater likelihood of stopping (~77% stopping probability). *t* test paired samples with Bonferroni correction; *P*-value annotation legend: *: 0.01 < *P* ≤ 0.05; **: 0.001 < *P* ≤ 0.01; ***: 0.0001 < *P* ≤ 0.001; ****: *P* ≤ 0.0001.

the iSPN-alone condition. Finally, when all three regions were stimulated simultaneously, we observed a 77% stopping probability, which is slightly higher than the iSPN-only stimulation. These results show that, as nodes higher up in the standard basal ganglia hierarchy are targeted, the efficiency of action cancellation increases. While aspects of the action suppression resulting from STN-driven inhibitory control (via direct excitation of the internal globus pallidus; GPi) and iSPN-driven control (via the long and short indirect pathways) are well understood, the mechanism by which Arky cells drive, or otherwise contribute, to this behavioral inhibition remains unclear.

Impact of Arkypallidal Neurons on Reactive Inhibition. To analyze how Arky neurons impact reactive inhibition, we measured how their activation alters the overall dynamics of the CBGT circuit, particularly its postsynaptic targets in the striatum. Stimulating Arky cells pushed the rest of the CBGT network into an overall movement-suppressive state (Fig. 2A). Notably, the dSPNs exhibited the strongest drop in firing rates due to Arky activation, followed by the iSPNs. Downstream, we observe that these changes result in an increase in GPi activity and, consequently, decreased activity in the thalamic targets of the basal ganglia.

This asymmetric influence of Arky stimulation on i/dSPN activity suggests that Arky neurons influence basal ganglia output by affecting the competitive balance between the direct and indirect pathways (16–18). To explore this idea further, we stimulated Arky cells while altering the strength of the reciprocal inhibitory collaterals between iSPNs and dSPNs. Gradually removing the inhibition provided by iSPNs to dSPNs during

Arky stimulation produced an increase in dSPN activity that, in turn, resulted in a reduction of the network's ability to withhold a decision ($F[5,29] = 36.25$, $P < 0.0001$; Fig. 2B and C) and produced faster RTs on failed stop trials ($F[5,29] = 17.42$, $P < 0.0001$; Fig. 2C). Interestingly, with the removal of iSPN inhibition of dSPN, Arky stimulation led to an overall reduction in Arky activity (Fig. 2B), which might seem counterintuitive. However, this effect is attributed to a recurrent loop between Arky cells and dSPNs: as dSPN firing intensifies, due to the release from inhibition from its iSPN afferents, dSPN subsequently exerts greater inhibition on Arky neurons, leading to a decrease in their activity. When we tested the reverse scenario, by gradually attenuating the inhibition exerted by dSPNs onto iSPNs during stimulation of the Arky population, we observed a subsequent rise in the activity of iSPNs. This change led to a marginal enhancement in the probability of successful stopping ($F[5, 29] = 2.44$, $P = 0.046$; Fig. 2D). Additionally, this also resulted in slightly longer RTs ($F[5,29] = 2.18$, $P = 0.07$; Fig. 2E). These results confirm that the suppression of actions induced by activation of Arky cells is moderated by a shift in the balance of power against the direct pathway and in favor of the indirect pathway.

Because they receive input from the STN and convey inhibitory output to the striatum, the Arky neurons are ideally positioned to be a central node in an ascending pathway that can modulate the descending control signals from the striatum that drive reactive inhibition in CBGT circuits (11). To further evaluate their influence, we simulated a lesion of Arky neurons by injecting a suppressive current into these cells while a stop signal was delivered to the STN cells, iSPNs, or both. In each experiment, we compared network responses with Arky cell

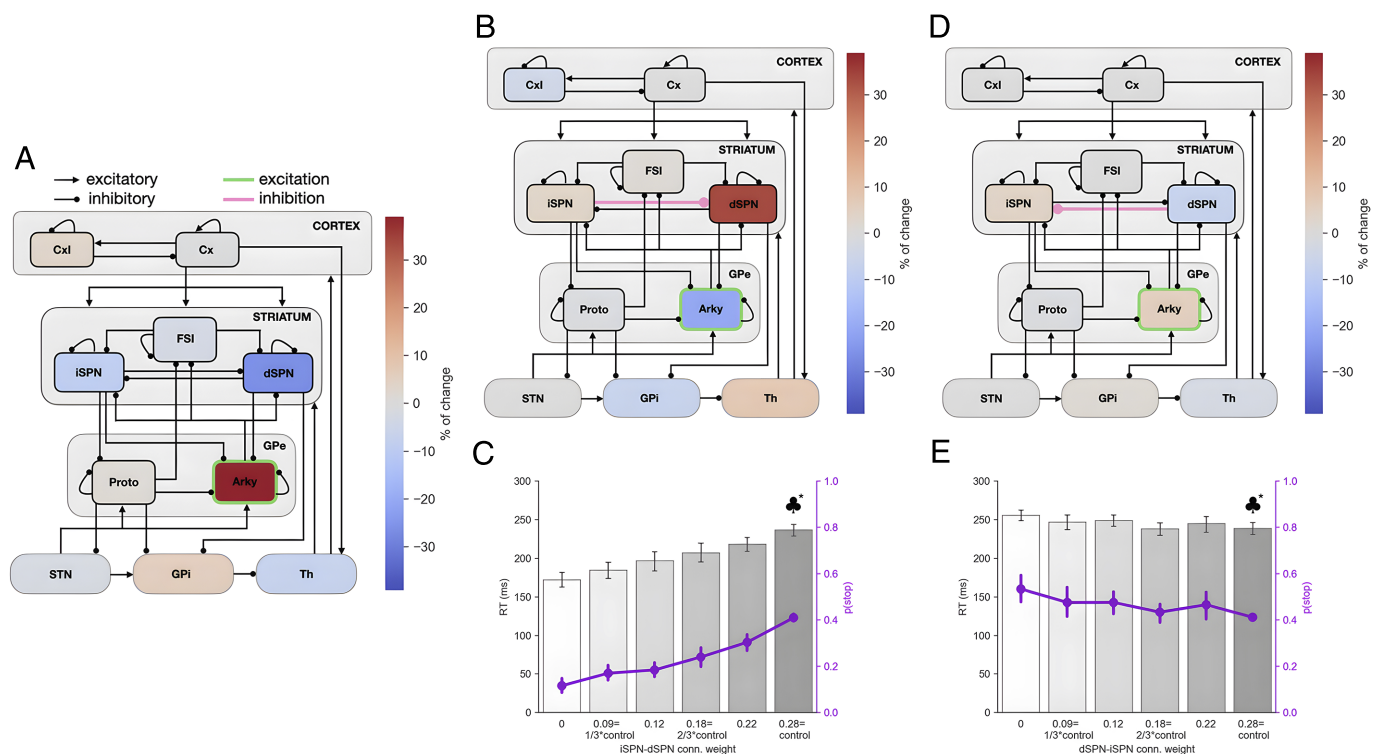


Fig. 2. Stimulation of Arky cells shifts the balance between striatal populations. (A) Stimulation of Arky neurons (green outline) induces a stronger decrease in dSPN firing than in iSPNs. (B) The change in the CBGT network's firing patterns during Arky stimulation (green), while the collaterals from iSPNs to dSPNs are individually attenuated (pink connections). Firing rate changes show the change between the two cases of extreme collateral connection strengths, 0.28 (control) and 0. (C) Changes in network's ability to suppress responses and in RTs when the experiment depicted in panel B is implemented in steps. (D) The change in the CBGT network's firing patterns during Arky stimulation (green), while the collaterals from dSPNs to iSPNs are individually attenuated (pink connections). The same formalism as in panel B is used. (E) Changes in network's ability to suppress responses and in RTs when the experiment depicted in panel D is implemented in steps. *♣ depicts baseline case.

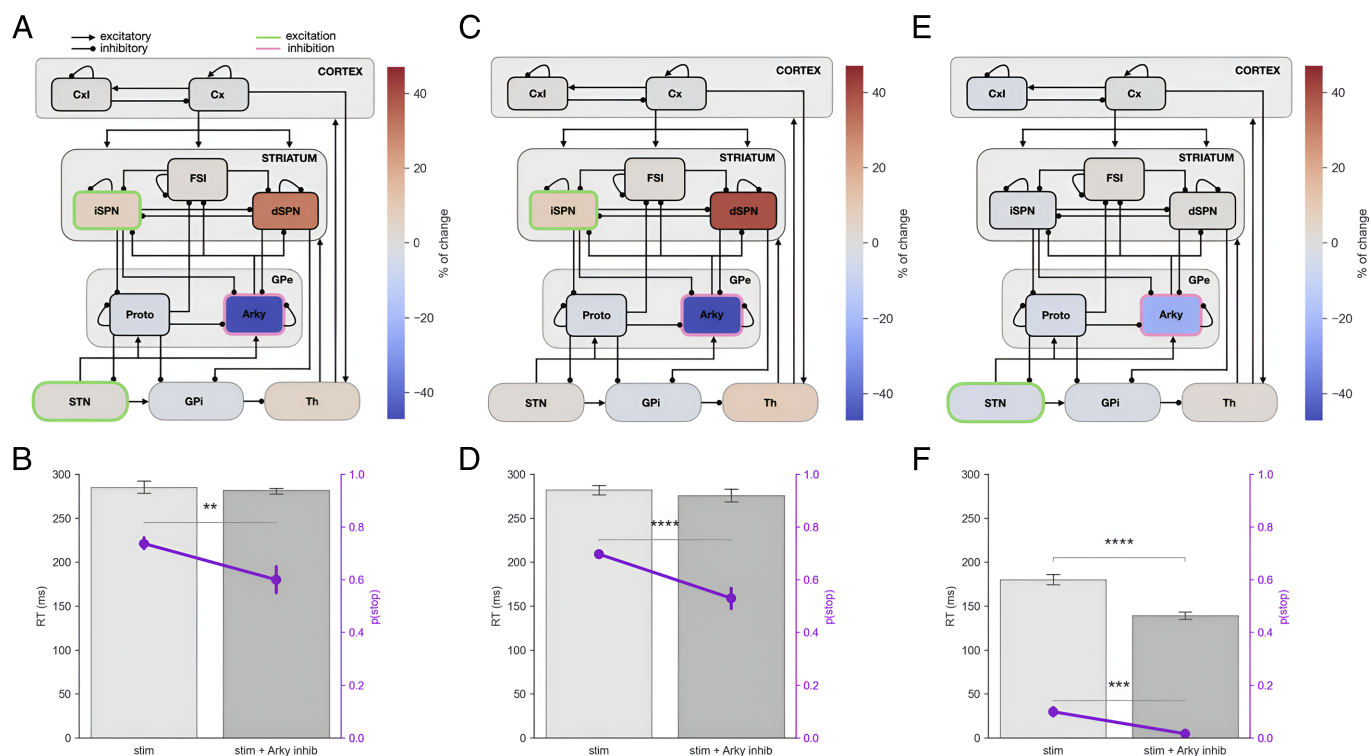


Fig. 3. Arky cells mediate ascending and descending information flow within the CBGT network in the context of reactive inhibition. (A) Network schematic of an experiment where Arky population activity is suppressed while STN and iSPNs are stimulated. Color codes show the changes in firing rates after suppression of the Arky neurons compared to before. (B) Stopping probability and RT across the task condition portrayed in panel A. (C) Network schematic of an experiment where Arky population activity is suppressed while iSPNs are stimulated. Color codes indicate firing rate changes after Arky neurons suppression. (D) Stopping probability and RT across the task condition portrayed in panel C. (E) Network schematic of an experiment where Arky population activity is suppressed while STN is stimulated. Color codes represent firing rate changes after Arky neurons suppression. (F) Stopping probability and RT across the task condition portrayed in panel E.

suppression (lesion) to conditions where the Arky cells were left unperturbed (control).

We started with the combined stimulation case (i.e., stimulation of both STN cells and iSPNs; Fig. 3A), where we observed a discernible decline in the likelihood of successful stops when the Arky cells were suppressed (stim: 0.74 ± 0.0116 (\pm SEM), stim + Arky inhib: 0.60 ± 0.0268 ; $t(9) = 4.44$, $P = 0.0016$; Fig. 3B). This effect was not reliably observed in the RTs (stim: 285 ± 4 , stim + Arky inhib: 282 ± 2 ; $t(9) = 0.94$, $P = 0.3721$; Fig. 3B). We next aimed to dissect the dynamics induced by the simultaneous stimulation of the two nuclei by independently activating each of them. We first looked at the involvement of Arky cells in the transmission of descending indirect pathway control signals originating from the iSPNs (Fig. 3C). Here, we observed similar effects as in the combined stimulation case, with a noticeable decrease in the likelihood of successful stops (stim: 0.70 ± 0.0060 ; stim + Arky inhib: 0.53 ± 0.0219 ; $t(9) = 6.99$, $P < 0.0001$; Fig. 3D). As before, a change was not consistently observed in RTs (stim: 282 ± 3 , stim + Arky inhib: 276 ± 4 ; $t(9) = 2.10$, $P = 0.065$; Fig. 3D). These results indicate two things. First, Arky cells play a role in modulating the effectiveness of descending control signals within the indirect pathway. Second, iSPNs play a dominant role in the effects observed from stimulating both STN neurons and iSPNs (Fig. 3A and B). We next tested the classical stop signal control model by activating the hyperdirect pathway via stimulation of the STN cells (Fig. 3E). Here, suppression of Arky neurons resulted in both a reduction of the network's ability to stop effectively (stim: 0.10 ± 0.0086 , mean \pm SEM; stim + Arky inhib: 0.01 ± 0.0075 ; $t(9) = 6.23$, $P = 0.0002$; Fig. 3F) and the RTs observed on

trials where stopping did not occur (stim: 180 ± 3 ; stim + Arky inhib: 139 ± 2 ; $t(9) = 9.06$, $P < 0.0001$; Fig. 3F). This outcome confirms that Arky cells also influence the effectiveness of hyperdirect pathway control, including on RTs. Although the hyperdirect pathway is traditionally viewed as a descending pathway, from STN to basal ganglia output nuclei, these results also indicate that their ascending component, gated by Arky cells that project to the striatum, significantly affects the network's capacity to stop or slow actions.

These findings suggest that the pallidostriatal pathways contribute to the bidirectional flow of inhibitory control signals within the CBGT circuit. To see how Arky cell suppression impacts the activity of the network, we also calculated the firing rate changes from before to after Arky suppression in each of the three conditions shown in Fig. 3. With the stop signal being delivered only to the STN neurons, Arky cell suppression had a relatively small impact on overall network activity (node colors in Fig. 3E). In contrast, for both iSPN stimulation conditions (Fig. 3A–C), suppressing Arky cells led to amplified activity in both SPN populations, with a stronger effect on dSPNs than iSPNs. These observations suggest that Arky neurons modulate the dynamics downstream of the striatum primarily by helping to suppress dSPN activity.

Mechanisms Underlying Arky Effects on Reactive Inhibition.

The preceding experiments show how pallidostriatal pathways likely influence striatal activity, and hence descending information flow, by shifting the relative dominance away from dSPNs and toward iSPNs. To directly test this idea, we drove reactive inhibition by delivering the stop signal to both iSPNs and Arky

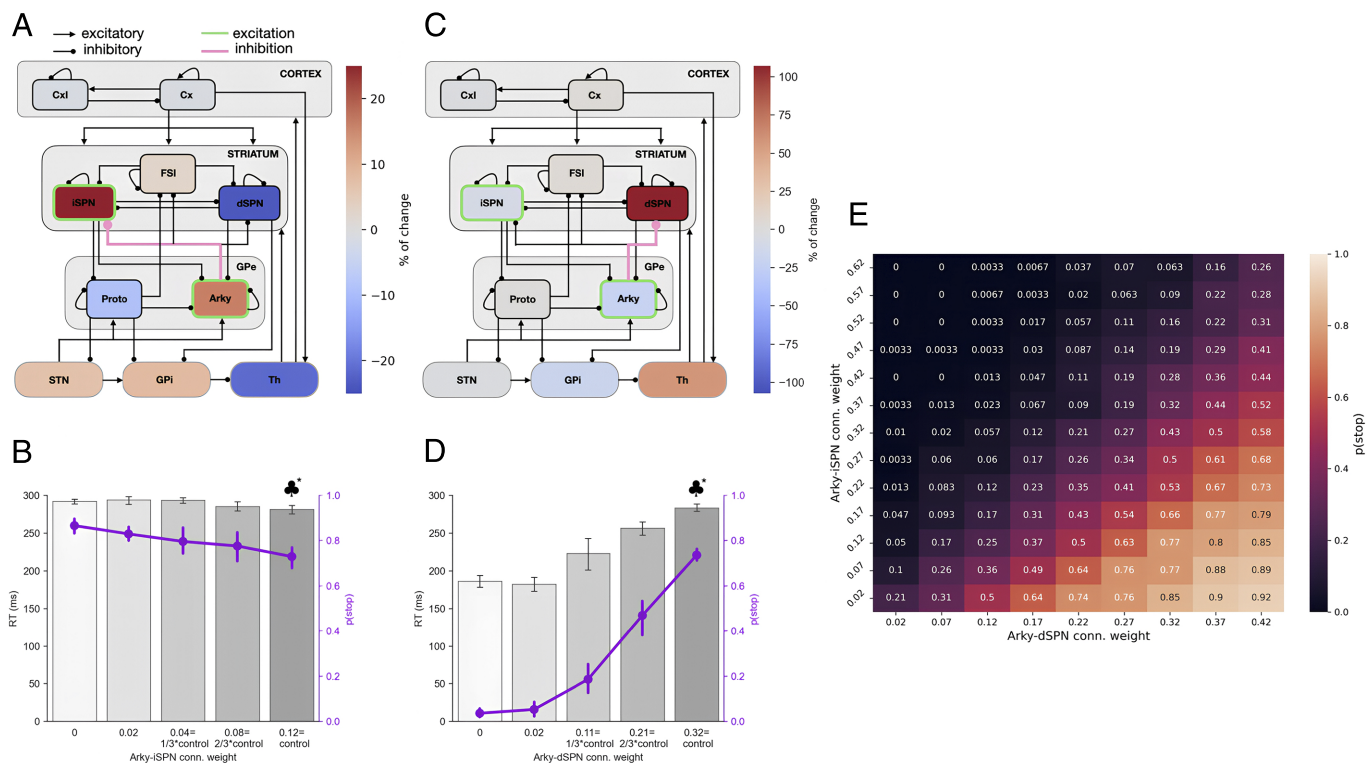


Fig. 4. Arky neurons shift the striatal balance of power due to differential inhibition of dSPNs and iSPNs. (A) Network firing schematics during Arky neuron and iSPN stimulation, with concurrent blocking of pallidal inhibitory input into iSPNs (in pink). Firing rate changes show the change between the two extreme conditions of 0 and 0.12 (control) for Arky → iSPN manipulation (panel A). (B) Evolution of network's ability to suppress responses and of RTs during the experiment depicted in panel A. (C) Network firing schematics during Arky neuron and iSPN stimulation, with concurrent blocking of pallidal inhibitory input into dSPNs (in pink). Firing rate changes show the change between the two extreme conditions of 0 and 0.32 (control) for Arky → dSPN manipulation (panel D). (D) Evolution of network's ability to suppress responses and of RTs during the experiment depicted in panel C. * depicts for baseline behavior. (E) Synaptic weight analysis to study the relative strengths of inhibitory projections from Arky cells to striatal populations. The effect of iSPN and Arky population stimulation grows with the ratio of Arky → dSPN to Arky → iSPN connection strengths.

cells while separately changing the efficacies of the pallidostriatal connections to the iSPNs and the dSPNs. As we reduced the strength of Arky GABAergic projections onto iSPNs, we observed an increase in iSPN activity. This, in turn, contributed to a further decrease in dSPN firing rates, as well as a drop in Proto cell activity (Fig. 4A). These changes produced an increase in GPi firing, subsequently leading to a reduction in thalamic activity and thereby enhancing the network's ability to suppress responses ($F[4,29] = 4.23$, $P = 0.005$; Fig. 4B), accompanied by longer RTs when responses were made ($F[4,29] = 4.31$, $P = 0.005$; Fig. 4B). Conversely, as we gradually reduced the Arky inhibition to dSPNs, we observed a dramatic increase in dSPN activity, which lowered the firing rates of both iSPNs and Arky neurons (Fig. 4C; note the change in scale of effects between Fig. 4A and C). This rise in dSPN activity resulted in decreased GPi activity, which in turn led to an amplification of thalamic firing (Fig. 4C). Consequently, the network failed to adequately suppress responses ($F[4,29] = 132.28$, $P < 0.0001$; Fig. 4D) and produced shorter RTs on missed stop trials ($F[4,29] = 50.22$, $P < 0.0001$; Fig. 4D). Together with Fig. 2A, these results suggest that Arky neuron inputs to dSPNs and iSPNs are instrumental in modulating the balance of power between these striatal populations, such that the bias of the network shifts to the indirect pathway as Arky cells increase their activity.

To provide a more thorough test of our hypothesis that the Arky cells tune the competition between direct and indirect pathways, we conducted a synaptic weight analysis, varying the relative degrees of Arky → iSPN and Arky → dSPN inhibition,

while delivering a stop signal to both iSPNs and Arky cell populations. As expected, boosting the relative inhibition of dSPNs over iSPNs increased the overall stopping probability (Fig. 4E), consistent with our hypothesis.

Discussion

Recent empirical observations have emphasized the contribution of Arky neurons in the rodent GPe for promoting action suppression (5–8). Yet how this control is implemented remains unclear. We constructed a biologically constrained spiking neural network model of the CBGT circuitry, using the available empirical evidence to define the connectivity and physiology of the model, to simulate performance in a normative version of the stop signal task. By reproducing the effects of activating three major stop-related targets within the CBGT circuit, we found that nodes higher in the CBGT hierarchy exhibited greater influence on action cancellation. Our results place pallidostriatal pathways as a central hub of the CBGT network, regulating the back-and-forth transfer of signals within the basal ganglia circuitry. In particular, our results predict that pallidostriatal pathways tune reactive control by reducing the relative influence of the direct pathway. This effect arises due to the presence of functionally stronger projections from Arky to dSPNs compared to iSPNs, which alters the competition between direct and indirect pathways.

Our simulation results align very closely with prior empirical observations. Schmidt et al. (32) discovered that STN and SNr

react swiftly to stop cues, well in advance of the stop signal RT. Their results suggest that STN activation may occur too rapidly to be fully responsible for preventing actions. Moreover, it may be insufficiently specific, as similar responses have also been observed for go cues in similar tasks (5, 33). Building on this evidence, Mallet et al. (5) proposed a two-step model for reactive stopping. In this model, the hyperdirect pathway initiates a rapid “Pause” signal, allowing time for a slower, separate “Cancel” process to occur within the striatum. Notably, an increase in firing rates has been observed in both Proto and Arky neurons following the presentation of a stop signal, with Arky neurons showing a more pronounced response than Proto cells, consistent with their involvement in halting actions. This observation was confirmed by Aristieta et al. (6), who achieved abrupt interruption of actions by optogenetically stimulating Arky neurons in rodents engaged in treadmill locomotion, an effect that the authors suggest is likely mediated through suppression of striatal activity. Pamukcu et al. (7) demonstrated that optogenetic stimulation of the axon terminals in the dorsal striatum from *Npas1*-expressing neurons in GPe, 60% of which are Arky neurons, decreased motor output. Collectively, these experimental findings underscore the pivotal contribution of the pallidostriatal pathways in inhibitory control. Importantly, our simulations build on these results by providing evidence that without Arky neuron involvement, the slowed RTs associated with STN stimulation would be lost, and the probability of stopping under iSPN stimulation would be reduced. Thus, Arky neurons appear to play a critical role in integrating control signals from both hyperdirect and top-down pathways.

Parameter values in our model are tuned to achieve realistic firing rates and were mostly carried over from past work (34–36); these are provided along with other model details and relevant experimental references in *SI Appendix*. Relative numbers of neurons across basal ganglia regions and some synaptic connectivity parameters in the model reflect the assumption that we model a single action channel, rather than an arbitrary portion of the cells in each basal ganglia population (see *SI Appendix* for details). For computational efficiency and to limit the number of unconstrained parameters within our model, we have run our simulations on a network of point neuron models without including axonal or synaptic delays. The inclusion of additional biological details in the model could provide insights about the roles of other features, such as specific voltage-gated ion channels, and might affect some quantitative aspects of stopping performance, but we do not expect that this would alter our qualitative findings.

Emerging evidence will likely continue to update our understanding of how Arky cells centrally mediate the ascending and descending flow of control signals in CBGT pathways. For example, there is some evidence to suggest that the Arky cells receive their own direct inputs from the cortex (37). Such inputs would extend the role of GPe beyond simple mediation of hyperdirect and direct/indirect pathway control signals. Other evidence contradicts this idea of direct cortical control of Arky cells, however, indicating no specific bias in cortical projections toward any GPe neuron subtype (38, 39). In addition, there may be monosynaptic connections from STN to striatum that facilitate the transmission of hyperdirect signals. The influence of these connections on the activity of SPNs remains uncertain, although there appears to be a significant impact on striatal parvalbumin interneurons (40). These and other emerging details may expand our view of the mechanisms of pallidostriatal control but will not change the fact that pallidostriatal pathways mediate ascending and descending control signals. Indeed, using

optogenetics to test our simulation and lesion experiments *in vivo* could provide critical tests of our model predictions and hence deeper insights into the contributions of CBGT pathways to reactive inhibition.

Materials and Methods

CBGT Network. The CBGT model is a computational, biologically inspired spiking neuronal network, comprising six distinct neural regions: the cortex, with excitatory (Cx) and inhibitory (Cxl) subpopulations; the striatum, including dSPNs, iSPNs, and FSLs; the GPe, segmented into Proto and Arky subpopulations; the STN; the GPI; and a thalamic component (Th). Fig. 1*B* illustrates the network's connectivity, where three main pathways can be distinguished. In the direct pathway, cortical inputs activate the dSPNs, which in turn inhibit the GPI, causing disinhibition of thalamic activity, potentially facilitating action selection. Conversely, the indirect pathway involves cortical inputs activating the iSPNs, which inhibit the components of the GPe and thereby impact populations throughout the basal ganglia through various polysynaptic interactions thought to have a net suppressive effect on action selection. By externally stimulating the STN, we also simulate the activation of the hyperdirect pathway. This third pathway is traditionally thought to operate independently of the striatum, directly regulating thalamic inhibition through cortical input to the STN and its excitatory influence on GPI. For more details on the network implementation, see ref. 41 and *SI Appendix*; see also ref. 11 for a review of experimental findings that justify the network structure used. Note that ref. 41 describes a framework that can implement competition between multiple action channels. Within this framework, in this study, we decided to consider just one action channel because this simplest case is sufficient to allow us to explore the relative contributions of different target populations to performance of the stop signal task.

Stop Signal Task. We implemented a computational version of a standard stop signal task (Fig. 1*A*), where the network must control the execution or suppression of an action, following the onset of imperative cues. The first cue presented corresponds to a “Go” stimulus, applied to the Cx, which drives the network toward a decision. During a trial, a decision is made when the thalamic firing rate reaches 30 Hz. If no decision is made within a trial window of 300 ms, then no choice is recorded and a successful inhibition occurs. 70 ms after the Go stimulus, another cue is presented: the “Stop” signal. We implemented this signal as a step up in the intensity of an excitatory input current that modulates the firing rate of each target population. In this computational study, we apply a stop signal current to distinct target populations implicated in the process of action suppression, thereby amplifying the activity of each targeted region. To measure any change in activity, we computed regional firing rates from the onset of the stop signal until the end of the decision phase. For a comprehensive understanding of the task, refer to our methods paper (41); refer also to *SI Appendix* for further details about the stop signal implementation. The stop signal current is characterized by several key parameters: a) amplitude, indicating the intensity of the applied stimulation; b) population, specifying the targeted CBGT region; c) onset, indicating the timing of the stimulation relative to the trial onset; d) duration, defining how long the stimulation lasts. The choice of these parameters influences the resulting stopping probability and RT distribution. For this study, we set the amplitude, onset, and duration parameters to establish a baseline condition with a stopping probability of approximately 75% (amplitude = 0.4 Hz, onset = 70 ms, and duration = 145 ms). The stopping probability was calculated by averaging the frequency of instances where no decisions were made across 10 threads, each consisting of 30 trials, resulting in a total of 300 trials.

Data, Materials, and Software Availability. The network codebase utilized in this study can be found on our GitHub repository and accessed at <https://github.com/CoAxLab/CBGTpy> (42). Detailed installation instructions and a comprehensive list of implemented functions can be found in the README.txt file within the repository. All datasets generated and analyzed during the course of this research, along with a demonstration demo, are openly available on GitHub at <https://github.com/gioissic/arky-stopsignal> (43).

ACKNOWLEDGMENTS. C.G. and C.V. are supported by the PCI2020-112026 and PCI2023-145982-2 projects, both funded by MCIN/AEI/10.13039/501100011033 and by the European Union "NextGeneration EU"/PRTR as part of the Collaborative Research in Computational NeuroScience (CRCNS) program. C.G. is also supported by the Conselleria de Fons Europeus,

Universitat i Cultura del Govern de les Illes Balears under Grant FPU2023-008-B. J.B. is supported by ANR-CPJ-2024DRI00039. T.V., J.B., and J.E.R. are partly supported by NIH Awards R01DA053014 and R01DA059993 as part of the CRCNS program. J.E.R. is partly supported by NIH Award R01NS125814, also part of the CRCNS program.

1. J. R. Wessel, Surprise: A more realistic framework for studying action stopping? *Trends Cogn. Sci.* **22**, 741–744 (2018).
2. A. Nambu, H. Tokuno, M. Takada, Functional significance of the cortico-subthalamo-pallidal 'hyperdirect' pathway. *Neurosci. Res.* **43**, 111–117 (2002).
3. A. R. Aron, R. A. Poldrack, Cortical and subcortical contributions to stop signal response inhibition: Role of the subthalamic nucleus. *J. Neurosci.* **26**, 2424–2433 (2006).
4. K. H. Fife *et al.*, Causal role for the subthalamic nucleus in interrupting behavior. *eLife* **6**, e27689 (2017).
5. N. Mallet *et al.*, Arkyapallidal cells send a stop signal to striatum. *Neuron* **89**, 308–316 (2016).
6. A. Arietia *et al.*, A disinaptic circuit in the globus pallidus controls locomotion inhibition. *Curr. Biol.* **31**, 707–721 (2021).
7. A. Pamukcu *et al.*, Parvalbumin+ and Npas1+ pallidal neurons have distinct circuit topology and function. *J. Neurosci.* **40**, 7855–7876 (2020).
8. R. Schmidt, J. D. Berke, A pause-then-cancel model of stopping: Evidence from basal ganglia neurophysiology. *Philos. Trans. R. Soc. B: Biol. Sci.* **372**, 20160202 (2017).
9. N. Mallet *et al.*, Dichotomous organization of the external globus pallidus. *Neuron* **74**, 1075–1086 (2012).
10. F. Fujiyama *et al.*, A single-neuron tracing study of arkyapallidal and prototypic neurons in healthy rats. *Brain Struct. Funct.* **221**, 4733–4740 (2016).
11. C. Giossi, J. E. Rubin, A. Gittis, T. Verstynen, C. Vich, Rethinking the external globus pallidus and information flow in cortico-basal ganglia-thalamic circuits. *Eur. J. Neurosci.*, 10.1111/ejn.16348 (2024).
12. J. Dong, S. Hawes, J. Wu, W. Le, H. Cai, Connectivity and functionality of the globus pallidus externa under normal conditions and Parkinson's disease. *Front. Neural Circ.* **15**, 645287 (2021).
13. L. Z. Fang, M. C. Creed, Updating the striatal-pallidal wiring diagram. *Nat. Neurosci.* **27**, 15–27 (2023).
14. C. D. Courtney, A. Pamukcu, C. S. Chan, Cell and circuit complexity of the external globus pallidus. *Nat. Neurosci.* **26**, 1147–1159 (2023).
15. A. Nambu, S. Chiken, External segment of the globus pallidus in health and disease: Its interactions with the striatum and subthalamic nucleus. *Neurobiol. Dis.* **190**, 106362 (2024).
16. K. Dunovan, T. Verstynen, Believer-skeptic meets actor-critic: Rethinking the role of basal ganglia pathways during decision-making and reinforcement learning. *Front. Neurosci.* **10**, 106 (2016).
17. J. G. Mikhael, R. Bogacz, Learning reward uncertainty in the basal ganglia. *PLoS Comput. Biol.* **12**, e1005062 (2016).
18. S. Bariselli, W. Fobbs, M. Creed, A. Kravitz, A competitive model for striatal action selection. *Brain Res.* **1713**, 70–79 (2018).
19. M. A. Vince, The intermittency of control movements and the psychological refractory period. *Br. J. Psychol.* **38**, 149 (1948).
20. J. S. Lappin, C. W. Eriksen, Use of a delayed signal to stop a visual reaction-time response. *J. Exp. Psychol.* **72**, 805 (1966).
21. F. Verbruggen *et al.*, A consensus guide to capturing the ability to inhibit actions and impulsive behaviors in the stop-signal task. *eLife* **8**, e46323 (2019).
22. A. V. Kravitz *et al.*, Regulation of parkinsonian motor behaviours by optogenetic control of basal ganglia circuitry. *Nature* **466**, 622–626 (2010).
23. G. E. Alexander, M. R. DeLong, P. L. Strick, Parallel organization of functionally segregated circuits linking basal ganglia and cortex. *Annu. Rev. Neurosci.* **9**, 357–381 (1986).
24. J. W. Mink, The basal ganglia: Focused selection and inhibition of competing motor programs. *Prog. Neurobiol.* **50**, 381–425 (1996).
25. M. R. DeLong, Activity of pallidal neurons during movement. *J. Neurophysiol.* **34**, 414–427 (1971).
26. A. H. Gittis *et al.*, New roles for the external globus pallidus in basal ganglia circuits and behavior. *J. Neurosci.* **34**, 15178–15183 (2014).
27. A. Abdi *et al.*, Prototypic and arkyapallidal neurons in the dopamine-intact external globus pallidus. *J. Neurosci.* **35**, 6667–6688 (2015).
28. V. M. Hernández *et al.*, Parvalbumin+ neurons and Npas1+ neurons are distinct neuron classes in the mouse external globus pallidus. *J. Neurosci.* **35**, 11830–11847 (2015).
29. A. Saunders *et al.*, A direct gabaergic output from the basal ganglia to frontal cortex. *Nature* **521**, 85–89 (2015).
30. V. L. Corbit *et al.*, Pallidostriatal projections promote β oscillations in a dopamine-depleted biophysical network model. *J. Neurosci.* **36**, 5556–5571 (2016).
31. M. Ketzef, G. Silberberg, Differential synaptic input to external globus pallidus neuronal subpopulations in vivo. *Neuron* **109**, 516–529 (2021).
32. R. Schmidt, D. K. Leventhal, N. Mallet, F. Chen, J. D. Berke, Canceling actions involves a race between basal ganglia pathways. *Nat. Neurosci.* **16**, 1118–1124 (2013).
33. D. Sharp *et al.*, Distinct frontal systems for response inhibition, attentional capture, and error processing. *Proc. Natl. Acad. Sci. U.S.A.* **107**, 6106–6111 (2010).
34. W. Wei, J. E. Rubin, X. J. Wang, Role of the indirect pathway of the basal ganglia in perceptual decision making. *J. Neurosci.* **35**, 4052–4064 (2015).
35. K. Dunovan, C. Vich, M. Clapp, T. Verstynen, J. Rubin, Reward-driven changes in striatal pathway competition shape evidence evaluation in decision-making. *PLoS Comput. Biol.* **15**, e1006998 (2019).
36. C. Vich, M. Clapp, J. E. Rubin, T. Verstynen, Identifying control ensembles for information processing within the cortico-basal ganglia-thalamic circuit. *PLoS Comput. Biol.* **18**, e1010255 (2022).
37. F. Karube, S. Takahashi, K. Kobayashi, F. Fujiyama, Motor cortex can directly drive the globus pallidus neurons in a projection neuron type-dependent manner in the rat. *eLife* **8**, e49511 (2019).
38. H. Jeon *et al.*, Topographic connectivity and cellular profiling reveal detailed input pathways and functionally distinct cell types in the subthalamic nucleus. *Cell Rep.* **38**, 110439 (2022).
39. V. Lillascharoen *et al.*, Divergent pallidal pathways underlying distinct parkinsonian behavioral deficits. *Nat. Neurosci.* **24**, 504–515 (2021).
40. K. Kondabolu *et al.*, A selective projection from the subthalamic nucleus to parvalbumin-expressing interneurons of the striatum. *eNeuro* **10**, ENEURO.0417-21.2023 (2023).
41. M. Clapp *et al.*, CBGTPy: An extensible cortico-basal ganglia-thalamic framework for modeling biological decision making. *bioRxiv* [Preprint] (2024). <https://doi.org/10.1101/2023.09.05.556301> (Accessed 4 August 2024).
42. M. Clapp *et al.*, CBGTPy: An extensible cortico-basal ganglia-thalamic framework for modeling biological decisions. *GitHub*. <https://github.com/CoAxlLab/CBGTPy>. Deposited 26 March 2024.
43. C. Giossi, J. Bahuguna, J. E. Rubin, T. Verstynen, C. Vich, Arkyapallidal neurons in the external globus pallidus can mediate inhibitory control by altering competition in the striatum. *GitHub*. <https://github.com/giossic/arky-stopsignal>. Deposited 30 April 2024.