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Representation of spontaneous movement by dopaminergic neurons is cell-type selective and disrupted in parkinsonism

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Abstract

Midbrain dopaminergic neurons are essential for appropriate voluntary movement, as epitomized by the cardinal motor impairments arising in Parkinson's disease. Understanding the basis of such motor control requires definitions of how the firing of different types of dopaminergic neuron relates to movement, and how this activity is deciphered in target structures like the striatum. By recording and labeling individual neurons in behaving mice, we show that the representation of brief spontaneous movements in the firing of identified midbrain dopaminergic neurons is cell-type selective. Most dopaminergic neurons in the substantia nigra pars compacta (SNc), but not in ventral tegmental area (VTA) or substantia nigra pars lateralis (SNL), consistently represented the onset of spontaneous movements with a pause in their firing. Computational modeling revealed that the movement-related firing of these dopaminergic neurons can manifest as rapid and robust fluctuations in striatal dopamine concentration and receptor activity. The exact nature of the movement-related signaling in striatum depended on the type of dopaminergic neuron providing inputs, the striatal region innervated, and the type of dopamine receptor expressed by striatal neurons. Importantly, in aged mice harboring a genetic burden relevant for human Parkinson's disease, the precise movement-related firing of SNc dopaminergic neurons and the resultant striatal dopamine signaling were lost. These data show that distinct dopaminergic cell types differentially encode spontaneous movement, and elucidate how dysregulation of their firing in early Parkinsonism can impair their effector circuits.

Significance

Deciphering the roles of midbrain dopaminergic neurons in the control of movement is not only critical for understanding of normal motor function, but also for defining the basis of motor dysfunction in Parkinson's disease. Yet, it has been widely viewed that the activity of these neurons is not related to movement. Here, we demonstrate that dopaminergic neurons signal the onset of spontaneous movement in a cell-type selective manner, and that these signals can be read out in transmitter and receptor activity dynamics in striatum, one of their principal targets. Importantly, these movement-related signals were lost in a mouse model of Parkinson's disease. Together, these data suggest that movement-related firing of dopaminergic neurons is important for precise motor control.

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Introduction

Dopamine is vital for normal motor function, as exemplified by the motor deficits arising from the dysfunction/degeneration of midbrain dopaminergic neurons in Parkinson's disease (PD). One prevailing view is that midbrain dopaminergic neurons guide purposeful actions through encoding value, for example, by conveying the difference between expected and actual reward (1–3). Although this function has been ascribed to all midbrain dopaminergic neurons, there is considerable functional heterogeneity across different cell populations in the ventral tegmental area (VTA; A10) and the substantia nigra *pars compacta* (SNc; A9) (4–7). For example, some dopaminergic neurons respond to novel or salient events, or during cognitive processes such as decision making and working memory (6, 8–10). Moreover, while it has generally been considered that the firing of these dopaminergic neurons does not consistently vary with movement (3, 11), there is evidence that the activity of putatively-classified dopaminergic neurons can change during movement execution in a heterogeneous manner (12–16). This in turn raises the possibilities that at least some types of movement might be differentially encoded by the firing of distinct populations of dopaminergic neuron, and that

dysregulation of such activity might contribute to motor impairment in PD prior to, or commensurate with, frank neurodegeneration.

To investigate whether and how different types of midbrain dopaminergic neuron represent movement, we recorded the firing of single dopaminergic neurons in awake, head-fixed mice during rest and spontaneous movement, and then juxtacellularly labeled each recorded neuron to verify its cell type. We observed that identified SNc dopaminergic neurons typically paused their firing at the onset of movement, whereas VTA dopaminergic neurons did not. Using *in silico* simulations of dopamine release dynamics, we show that brief, movement-related changes in dopaminergic neuron firing can be reliably 'read out' in striatum as robust changes in dopamine concentration and receptor signaling. Notably, movement-related pauses in SNc neuron firing, and the resultant changes in dopamine signaling, were lost in parkinsonian mice, further supporting a role for this patterned activity in movement.

Results

To define the activity of dopaminergic neurons with high spatiotemporal resolution during rest and movement, action potentials fired by individual cells were extracellularly recorded in untrained, head-fixed mice. Mice were placed on a running wheel and recordings were made during rest or during brief (<1 s) spontaneous movements where the mouse altered its position on the running wheel in the absence of any overt reward or other external cue (17). We focused our analyses on such movements for two reasons: First, to avoid confounds arising from the challenges of distinguishing movement-related neuronal activity from that related to reward and/or external cues. Secondly, brief movements were less likely to destabilize single-cell recordings and thus, facilitated the subsequent juxtacellular labeling of neurons with Neurobiotin; the latter was used to unambiguously locate recorded neurons and determine whether they were dopaminergic by *post hoc* assessment of tyrosine hydroxylase immunoreactivity (Fig. 1A). We reasoned that, despite the heterogeneous kinematics of such

brief voluntary movements, any consistent neuronal responses that emerged would reflect general organizational or coding principles of dopaminergic neurons. In support of this, we observed that the majority of identified SNc dopaminergic neurons dramatically and consistently reduced their firing rate at movement onset (Fig. 1 *A* and *B*).

The firing rate of most SNc dopaminergic neurons decreases at movement onset

To compare movement-related changes in firing rate between neurons, we converted firing rates to z-scores; when all SNc neurons ($n = 15$) were considered together, they exhibited a significant decrease in their mean population firing rate at movement onset (Fig. 1*B*). When considered individually, 11 of 15 SNc dopaminergic neurons showed significant decreases in firing rate during movement onset (defined as the first 160 ms of each movement; Fig. 1*C*), whereas the remaining 4 neurons showed no change during the onset period (Fig. 1*D*). A minority of all SNc neurons (4 of 15) exhibited significant rate increases during the 'pre-movement' period (160 ms immediately preceding movement); however, these neurons also exhibited decreases in mean firing at movement onset (Fig. S1*A*). Importantly, the occurrence of a movement-related pause in firing was not dependent on any pre-movement rate increase (Fig. S1*B*), suggesting that the pause was not simply a refractory period following any increased firing just before movement. Comparison of interspike intervals (ISIs) confirmed a genuine pause in firing (Fig. 1*E*); the mean ISI during movement onset was significantly longer than that during baseline, but baseline and pre-move ISIs were similar. To further examine whether the firing-rate variations of SNc neurons around brief movements were sufficiently distinct from stochastic rate changes occurring between movements, we analyzed the area under the receiver operating characteristic (AUROC) curve of each SNc neuron to test whether the firing rate of each neuron could be used to correctly classify the occurrence of spontaneous movements. The firing of most SNc neurons (11 of 15) predicted movement significantly above chance (mean AUROC of 0.65 ± 0.02 ; $n = 11$), suggesting their firing-rate variations around movement are distinct enough to encode information.

We also explored whether SNc dopaminergic neurons represented the end of a movement, but we found no significant changes in firing rate following movement (Fig. S2A), suggesting that the activity we observe specifically signals the onset of movement, rather than indiscriminately representing a transition between states of mobility and immobility. To examine whether decreases in SNc neuron firing rates at movement onset were specific to brief movements, we also analyzed neuronal activity recorded during longer spontaneous movements (> 1s), which typically involved the animal walking or running on the wheel. The decreased firing of SNc neurons that occurred at the onset of brief movements also occurred at the onset of the long-duration movements (Fig. S2B), confirming that movement representation by SNc neurons extends to different types of spontaneous movement. We recorded neurons at different locations within the SNc (Fig. 1H), but found no significant relationships between firing properties and mediolateral or anteroposterior SNc locations of the neurons we sampled (Fig. S3). Taken together, these data show that most SNc dopaminergic neurons encode spontaneous movement with a pause in firing.

Distinct dopaminergic cell types differentially encode movement

Experiments in primates have shown that the responses of putatively-classified dopaminergic neurons to task-related stimuli varies according to location along a mediolateral axis (4, 8). We hypothesized that encoding of spontaneous movement by dopaminergic neurons might be cell-type selective. The precise localization of recorded neurons (afforded by juxtacellular labeling) allowed us to unambiguously test this hypothesis. Thus, in addition to SNc neurons, we also recorded from dopaminergic neurons in the lateral VTA (the parabrachial pigmented area; Fig. 2A, B, and G) and the substantia nigra *pars lateralis* (SNL; Fig. 2C, D, and G). Dopaminergic SNc neurons predominantly innervate the dorsal striatum, whereas lateral VTA neurons preferentially project to the nucleus accumbens, and SNL neurons project to several limbic targets (18). During periods of alert rest, VTA and SNL neurons fired at similar rates to those of SNc neurons (Figs. 1F and 2E; $p > 0.05$, $n = 14$ VTA neurons, 5 SNL neurons, and

16 SNc neurons, one-way ANOVA) but firing of SNL neurons was significantly more irregular (as assessed by CV2) than SNc neurons (Figs. 1G and 2F; $p < 0.05$, ANOVA on ranks with Dunn's *post hoc*). Unlike SNc neurons, neither VTA nor SNL neurons showed significant average responses during the movement onset period (Fig. 2B and D). A minority of VTA dopaminergic neurons (5 of 14), and most SNL neurons (4 of 5), significantly increased their firing rate immediately preceding movement (Fig. S1), resulting in average pre-movement increases at the population level (Fig. 2B and D). These differences in the timing, polarities and relative magnitudes of responses of SNc, VTA and SNL neurons did not arise from any systematic differences in the movements recorded with each cell type (average duration of movement: $p > 0.05$, ANOVA on ranks). Taken together, these data indicate that firing of midbrain dopaminergic neurons around spontaneous movements is cell-type selective.

Brief pauses in SNc neuron firing cause transient reductions in striatal dopamine levels

It is important to understand whether behavior-related changes in the firing of populations of dopaminergic neurons translate to fluctuations in striatal dopamine concentration. Currently, *in vivo* detection of increases and decreases of extracellular dopamine concentration at subsecond resolution (*i.e.* with fast-scan cyclic voltammetry (FCV)) has not yet been well established in dorsal striatum. To overcome this limitation, we employed a biophysical computational model of dopamine release recently developed for rat striatum (19–21); we adjusted SNc neuron innervation to model the dorsolateral mouse striatum (22), but left all other parameters unchanged. Using the spike trains of all our recorded SNc neurons as 'inputs' for the model, we examined how SNc neuron firing shaped dopamine release relative to movement (Fig. 3A). The model predicted that the baseline firing of SNc neurons results in a dopamine 'tone' of ~60 nM (Fig. 3B). Transient increases in the average firing of SNc neurons immediately preceding movement (see above) caused a significant increase in dopamine concentration (~20 nM). This was followed by a significant decrease in dopamine (~20 nM below baseline) during movement onset (Fig. 3B), *i.e.* the point at which SNc neurons

paused. To test whether such decreases were biologically plausible, we used FCV to measure extracellular dopamine concentration in the dorsal striatum *ex vivo* (evoked by local stimulation at 6 Hz to approximate the baseline firing rate of SNc dopaminergic neurons; see Fig. 1F). Brief pauses in stimulation (of a duration similar to the ISI during move onset (see Fig. 1E)) resulted in significant decreases in extracellular dopamine concentration (~20 nM; Fig. S4), indicating that movement-related pauses in neuron firing can indeed be reported as changes to striatal dopamine.

Our model predicts that movement-related firing of SNc neurons will alter dorsal striatal dopamine levels immediately before and during movement onset. However, the effect that this has on striatal neurons will depend upon the dopamine receptors that they express. Striatal spiny projection neurons (SPNs) can be grossly subdivided into ‘direct pathway’ SPNs (dSPNs), which express D1 dopamine receptors, and ‘indirect pathway’ SPNs (iSPNs) that express D2 receptors (23). Although both D1 and D2 receptors can exist in high-affinity and low-affinity states (24), intracellular signaling cascades in dSPNs appear to be activated by high levels of dopamine via D1 receptors, whereas intracellular signaling in iSPNs is inhibited by basal levels of dopamine acting at D2 receptors (25, 26). We therefore used the model to examine how the predicted movement-related changes in striatal dopamine concentration would activate low-affinity ($EC_{50} = 1 \mu\text{M}$) D1 receptors and high-affinity ($EC_{50} = 10 \text{ nM}$) D2 receptors. The predicted activity of D1 receptors closely matched the dopamine concentration profile, resulting in a small but significant increase in D1 receptor activity preceding movement, followed by a significant decrease during movement onset (Fig. 3C). Because D2 receptor activity was high at rest, the increase in dopamine concentration preceding movement was not matched by a significant increase in D2 receptor activity (Fig. 3D). However, the predicted decrease in dopamine concentration during movement onset resulted in a proportionally larger decrease in D2 receptor activity (~15%; Fig. 3D). It has recently been demonstrated that D2 receptors coupled to exogenous GIRK channels can exist in a low-affinity state (27). Our

model indicates that any low-affinity D2 receptors would not only be sensitive to the pause in SNc neuron firing but also to the pre-movement increase in dopamine.

The movement-related responses of VTA neurons differed to those of SNc neurons; we therefore modeled how VTA neuron firing would affect dopamine signaling in their principal target, the nucleus accumbens. In contrast to the scenario simulated for dorsal striatum receiving SNc neuron inputs, dopamine concentration and D1 receptor activity in the nucleus accumbens peaked during movement whereas D2 receptor activity was unchanged during movement (Fig. S5). Taken together, these data illustrate how brief, movement-related changes in the firing rates of midbrain dopaminergic neurons can lead to rapid and robust changes in striatal dopamine signaling. However, our data reiterate that the precise nature of movement-related signaling depends on the type of neuron providing inputs (SNc vs. VTA), the striatal region innervated (dorsal striatum vs. accumbens) and the type of dopamine receptor expressed by striatal neurons (D1 vs. D2).

Movement-related pauses in SNc neuron firing are lost in parkinsonian mice

Our experiments above indicate that the movement-related pauses in SNc neuron firing and the associated changes in striatal dopamine release could be important for signaling movement. Thus, one might expect that such firing patterns would be altered in cases when movement and dopamine neuron function are abnormal e.g. in Parkinson's disease. To test this prediction, we used a transgenic mouse model of PD (*SNCA-OVX* mice) in which moderate overexpression of human α -synuclein (a human-disease relevant genetic burden) leads to a slow, progressive phenotype that recapitulates many of the cardinal features of PD (28). Although aged *SNCA-OVX* mice have normal gross motor function (*i.e.* they perform spontaneous movements), they have impaired motor precision, resulting in foot-slips on the balance beam (28). To assess the neural representation of movement in these parkinsonian mice, we recorded and labeled SNc dopaminergic neurons in aged (23-27 month-old) *SNCA-*

OVX mice and their littermate controls (*Snca*^{-/-} mice). We have previously reported that the mean firing rate of SNc neurons is ~30% lower in anesthetized SNCA-OVX mice compared to littermate controls (28); we found that this phenotype was maintained in awake mice during alert rest (Fig. S6). At movement onset, SNc neurons in *Snca*^{-/-} littermate controls exhibited the same average reduction in firing rate at movement onset as those in wild-type mice ($p > 0.05$, $n = 15$ neurons in wild-type and 11 in *Snca*^{-/-} mice, Mann-Whitney rank sum), with 8 of 11 neurons showing significant decreases in firing rate (Fig. 4A and B). Correspondingly, the mean ISI of these neurons during movement onset was also longer than the ISIs during baseline and pre-movement periods (Fig. 4E). In contrast to control mice, the mean movement-related firing of SNc neurons in the parkinsonian SNCA-OVX mice was not significantly different from baseline (Fig. 4D). Furthermore, ISIs at movement onset were not significantly longer than baseline (Fig. 4F). Only 4 of 12 SNc neurons in SNCA-OVX mice exhibited significant decreases in rate, with the remaining neurons showing either no movement-related changes (5 of 12) or aberrant rate increases at movement onset (3 of 12; such increases were not observed in wild-type or *Snca*^{-/-} mice). To ensure that this loss of movement-related reductions in firing of SNCA-OVX dopaminergic neurons was not the result of a ‘floor effect’ from their lower firing rates, we calculated the threshold rate that each neuron would need to cross to reach significance. For 11 of 12 neurons, threshold was above the lowest mean firing rate observed in SNCA-OVX mice during onset, suggesting they had not hit a floor in their rate (the remaining neuron significantly increased firing rate at onset). In summary, these data provide the first direct evidence that the “real time” encoding of behavior by the firing of surviving dopaminergic neurons is perturbed in Parkinsonism.

Defining how altered movement-related firing of dopaminergic neurons impacts on striatal dopamine dynamics is essential for understanding the neuronal basis of the motor symptoms of PD. We therefore input spike trains recorded from all SNc neurons in littermate control and parkinsonian mice into our computational model. Dopamine signaling modeled in the dorsal striatum of control *Snca*^{-/-} control mice was similar to that in wild-type mice, with

striatal dopamine concentration, D1 receptor activity and D2 receptor activity decreasing at movement onset (Fig. 5A-C). However, when release was modeled using spike trains recorded from *SNCA-OVX* mice, not only was the dopamine tone lower at rest (as would be expected given the lower firing rate of SNc neurons in these mice), there were also no significant movement-related decreases in dopamine concentration or receptor activity (Fig. 5A-C). This suggests that, in the parkinsonian mice, the loss of movement-related dopaminergic neuron firing is reflected in the striatum as abnormally static dopamine release during movement. Aged *SNCA-OVX* mice not only exhibit altered SNc neuron firing, but they also lose ~30% of their dopaminergic SNc neurons and are impaired in their ability to release dopamine in dorsal striatum (28). To examine how these two additional deficits might interact with aberrant movement-related SNc neuron firing in parkinsonian mice, we incorporated these abnormalities into the model. The cumulative effect was even lower dopamine tone and receptor activity, and further blunting of the modeled movement-related dopamine signaling in striatum (Fig. 5D-F).

Discussion

Here, we define changes in the firing of neurochemically-identified dopaminergic neurons around the onset of spontaneous movement. We show a pause in firing at movement onset in SNc neurons and an increase in the mean activity of VTA and SNL neurons just before movement. Importantly, our *in silico* modeling predicts that these movement-related changes in SNc neuron firing will be 'read out' in the dorsal striatum as rapid and robust changes in dopamine concentration and receptor signaling. Moreover, the movement-related pause in SNc neuron firing and resultant changes in dopamine signaling are lost in parkinsonian mice, suggesting these fine temporal dynamics are important for motor control.

While the role of dopaminergic neurons in encoding reward, salience and aversion is well established, the prevailing view from task-based recordings in primates is that

dopaminergic neuron firing does not systematically change on fine time scales during movement (3). However, recent reports suggest that the firing of putative dopaminergic neurons in both rodents and primates is altered during trained movements (12–15). Our data show that the activity of identified dopaminergic neurons (in SNc, VTA and SNL) also changes around the spontaneous movements made by untrained mice in the absence of any overt cues or reward. Recordings of putative dopaminergic neurons have reported diversity in the polarity of movement-related rate changes, with some neurons increasing and others decreasing their firing rate (14, 15). Framing such diversity in terms of identified cell types is clearly important. By unambiguously defining the locations and neurochemical properties of our recorded neurons (using juxtacellular labeling), we demonstrate that distinct dopaminergic cell types respond differently during discrete phases of movement; SNc neurons represent the onset of movement with a pause in their firing, whereas VTA and SNL neurons show no change in firing rate during this period. Dopaminergic neurons not only exhibit heterogeneity in their properties and connectivity (5–7, 29–32), but also functionally, with medially-located neurons signaling value, and more lateral neurons encoding salience and cognitive significance (4, 8, 33). Here, we advance the notion of functional heterogeneity by showing that some modalities encoded by dopaminergic neurons can be defined according to well circumscribed subpopulations rather than as a spatial gradient in signaling.

Previous work has shown that some dopaminergic neurons signal aversion (or cues predicting it) through a reduction in firing rate (5, 34, 35). There are several lines of evidence to suggest that the movement-associated decreases in the firing of SNc neurons that we observed are not related to aversion or a ‘negative prediction error’. First, compared to VTA neurons (4, 6, 34–36), SNc neurons exhibit relatively poor encoding of aversive stimuli and negative prediction errors (37–39). Moreover, we observed movement-related decreases in the firing of SNc neurons but not of VTA neurons, which is the opposite of what would be expected. Second, not only did fewer SNc neurons in parkinsonian mice display movement-related decreases in firing, some neurons increased firing. If pauses in firing were encoding

aversion or prediction errors, one would expect to observe the same pauses in *SNCA-OVX* mice, because these mice do not have abnormal anxiety or cognitive phenotypes (28). Thus, our findings support work showing that some dopaminergic neurons can use decreases in firing rate for encoding information (4, 6, 34–36) and extend this concept to include their representation of spontaneous movement. It would be important to test in the future whether our findings extend to trained animals performing movement sequences embedded in a temporal framework of cues and rewards (e.g. in operant tasks).

Because dopaminergic neurons fire in the absence of excitatory synaptic inputs (7), the movement-related reduction in firing rate of SNc neurons is likely to be mediated by increased inhibitory input rather than suppression of excitatory drive (40). Around 50% of synapses made with SNc neurons are GABAergic (41) and these originate from numerous sources including the substantia nigra *pars reticulata* (SNr), the globus pallidus (GPe), the superior colliculus, the rostromedial tegmental nucleus, and SPNs located in striosomes (33, 42). However, it has yet to be determined which of these diverse afferents convey appropriately timed, movement-related signals to inhibit dopaminergic neuron firing.

Because reduced dopamine levels in PD are ostensibly anti-kinetic, one might have expected *a priori* that dopaminergic neurons would increase their firing during movement; instead, we find movement-related decreases in SNc neuron firing. What then is the role of these movement-related pauses in firing? *SNCA-OVX* mice show a loss of movement-related SNc neuron firing in association with a loss of motor precision; however, these mice, which model early stages of Parkinsonism, do not show gross motor abnormalities. As such, pauses in firing may not be necessary for initiation of movement but might instead be important for precision of movement. While dopamine is generally thought to play an indirect modulatory role in shaping the accuracy of future movements (43), it is worth noting that the timescale at which dopamine acts at downstream molecular effectors is consistent with a role in dopamine supporting selection of ongoing movements (with activation of striatal D2 autoreceptors or potassium channels occurring at around 50 ms (27, 44)). Our computational model indicates

that dorsal striatal D2 receptor activity would be disproportionately impacted by pauses in SNc neuron firing, thereby reducing D2 receptor-mediated suppression of iSPN activity in dorsal striatum. In models of action selection (45, 46), such disinhibition is thought to suppress 'competing' movements and thus pauses in firing could act to maintain movement precision. This said, our data also suggest this scheme might not hold in ventral striatum; representation of movement by VTA and SNc dopaminergic neurons is different, and the resultant dopamine signaling in nucleus accumbens should be distinct from that in dorsal striatum. Moreover, accumbens SPNs are not as clearly organized into direct and indirect pathways (47). Further complexity arises from the recent finding that dopaminergic VTA and SNc neurons also co-release GABA (48). Although the influence of GABA release caused by baseline firing of dopaminergic neurons *in vivo* is not yet clear, one might expect GABA release resulting from pre-movement SNc neuron firing to contribute to inhibition of both dSPNs and iSPNs, which would then be disinhibited at movement onset by the pause in SNc neuron firing. Such patterns of inhibition might be expected to sharpen and coordinate dSPN and iSPN activity.

In conclusion, we not only show that midbrain dopaminergic neurons can encode spontaneous movement with temporally-precise changes in their firing, but also that such encoding is cell-type selective. Neurons located in SNc, the dopaminergic cell population that is particularly vulnerable to degeneration in PD (49), signal movement onset with a pause in firing, whereas more resistant populations (VTA and SNL) do not. Alteration of the movement-related firing of SNc neurons and the resultant loss of dopamine signaling in experimental Parkinsonism suggest the novel activity dynamics we define here are important for the control of voluntary movement.

Materials and methods

All experimental procedures on animals were conducted in accordance with the Animals (Scientific Procedures) Act, 1986 (United Kingdom). Experiments were performed using 3–4

month-old male C57Bl6/J mice or 23–27 month-old male *SNCA-OVX* mice and male *Snca*^{-/-} littermates.

***In vivo* electrophysiological recording, juxtacellular labeling and data analysis**

Extracellular recordings were made from individual dopaminergic neurons in head-fixed mice positioned upon an Ethofoam running wheel (17). After recording, each neuron was juxtacellularly labeled with Neurobiotin (17, 28). After perfuse fixation, free-floating coronal sections (50 μm) were prepared, and Neurobiotin-labeled neurons were revealed with Cy3-conjugated streptavidin and tested for expression of tyrosine hydroxylase (TH) by indirect immunofluorescence (see *SI Materials and Methods*). To examine the movement-related firing of dopaminergic neurons, we focused our analyses on brief, self-initiated, spontaneous movements which occurred as a result of the animal adjusting its position on the wheel. Such movements were defined as those involving forelimb movement (determined from video recordings) and with a duration <1 s. Movement periods were determined using a combination of EMG (measured from cervical muscles) and videos of behavior (30 frames/s). Only neurons recorded during the spontaneous execution of ≥ 5 such movement periods were considered for further analysis of movement-related firing. Changes in movement-related activity were considered significant when firing rate crossed a threshold of baseline mean ± 2 SD during the defined movement period.

Computational model of striatal dopamine transmission

We used a computational model of dopamine volume transmission to calculate the extracellular dopamine levels and estimate the activation of postsynaptic signaling cascades (19, 20). The model was driven by spike input of an ensemble of recorded dopaminergic neurons (see *SI Materials and Methods*). All movement epochs were averaged to determine the mean single-cell response, then all responses were averaged to obtain mean dopamine concentrations and D1 and D2 receptor activities. In the model, peak dopamine release and uptake scales with density of release sites; to model the intact mouse dorsolateral striatum,

we adjusted innervation to 0.19 terminals per μm^3 , which gave a volume-averaged uptake $V_{\text{max}} = 7.4 \mu\text{M/s}$ and a dopamine transient evoked by a single pulse of 260 nM (22). To model ~30% reduction of evoked dopamine release and ~30% loss of dopaminergic SNc neurons that develops in aged *SNCA-OVX* mice (28), we reduced vesicular maximal release probability from 15% to 10% and the number of neurons driving the model by 30%, respectively.

Author contributions

P.D.D. and P.J.M. conceived and designed research with input from all other authors; P.D.D. performed all electrophysiological experiments and related analyses; J.K.D. performed computational modeling; Voltammetry experiments were performed by K.A.J.; P.D.D. wrote the paper with input from P.J.M. and all other authors.

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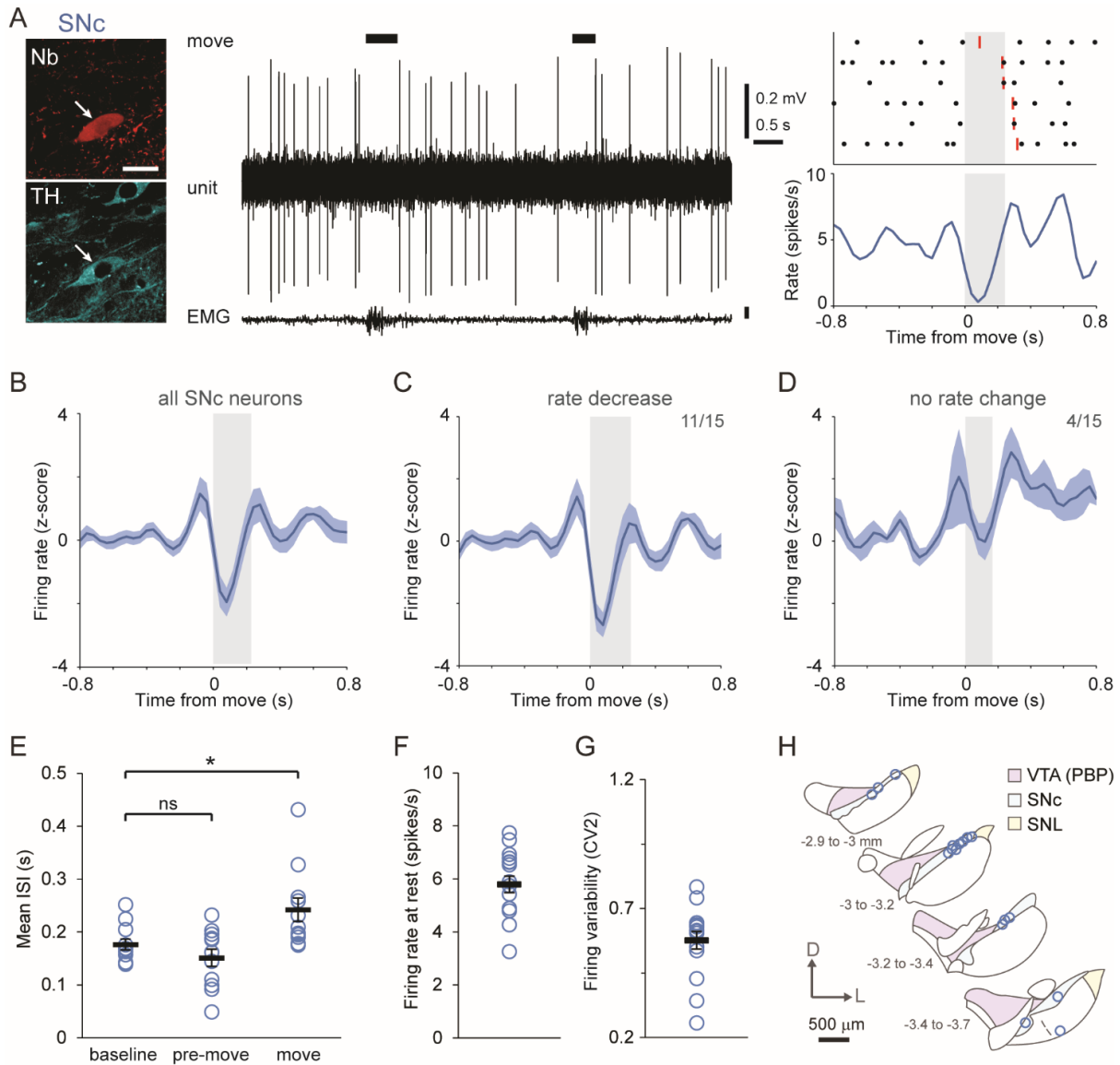


Fig. 1. Dopaminergic SNc neurons exhibit a pause in firing during the onset of spontaneous movement. (A) Example single-unit activity (middle) and peri-event time histogram (PETH, right, with corresponding raster plot above) from an identified dopaminergic SNc neuron (far left; scale bar, 20 μ m) during rest and spontaneous movement (latter denoted by black bars, determined from video and electromyogram (EMG) activity). The ends of individual movement epochs are denoted in rasters by red lines and mean movement duration by gray shading. After recording, each neuron was juxtacellularly labeled with Neurobiotin (Nb) to identify its dopaminergic nature (by immunoreactivity to tyrosine hydroxylase, TH) and confirm its location. (B–D) Mean normalized PETHs \pm SEM. On average, SNc neurons ($n = 15$) transiently increased their activity just before movement, and then paused their firing at the movement

onset (*B*); 11 SNc neurons significantly decreased their rate during movement onset (*C*) and 4 did not significantly change their rate (*D*). (*E*) Mean interspike interval (ISI) during the baseline, pre-move (ISIs ending in the 100 ms before movement) and movement periods (ISIs starting in the 100 ms preceding movement and ending after movement onset). The ISI during movement onset was significantly longer than baseline ISIs ($p < 0.01$, $n = 11$ neurons that met analysis criteria (see *SI Materials and Methods*), one-way RM ANOVA with Dunnett's *post hoc*). (*F–G*) Firing rate (*F*) and variability (*G*; quantified by CV²) of all SNc neurons ($n = 16$) during alert rest. (*H*) Schematic coronal sections (adapted from 50) denoting locations within the SNc of all recorded and identified dopaminergic neurons. Distance from Bregma is shown on left. VTA, ventral tegmental area; PBP, parabrachial pigmented area of the VTA; SNL substantia nigra *pars lateralis*; SNc substantia nigra *pars compacta*; D, dorsal; L, lateral. Data are represented as mean \pm SEM; * $p < 0.05$; ns, not significant. Scale bars for EMG are the same as for unit recordings.

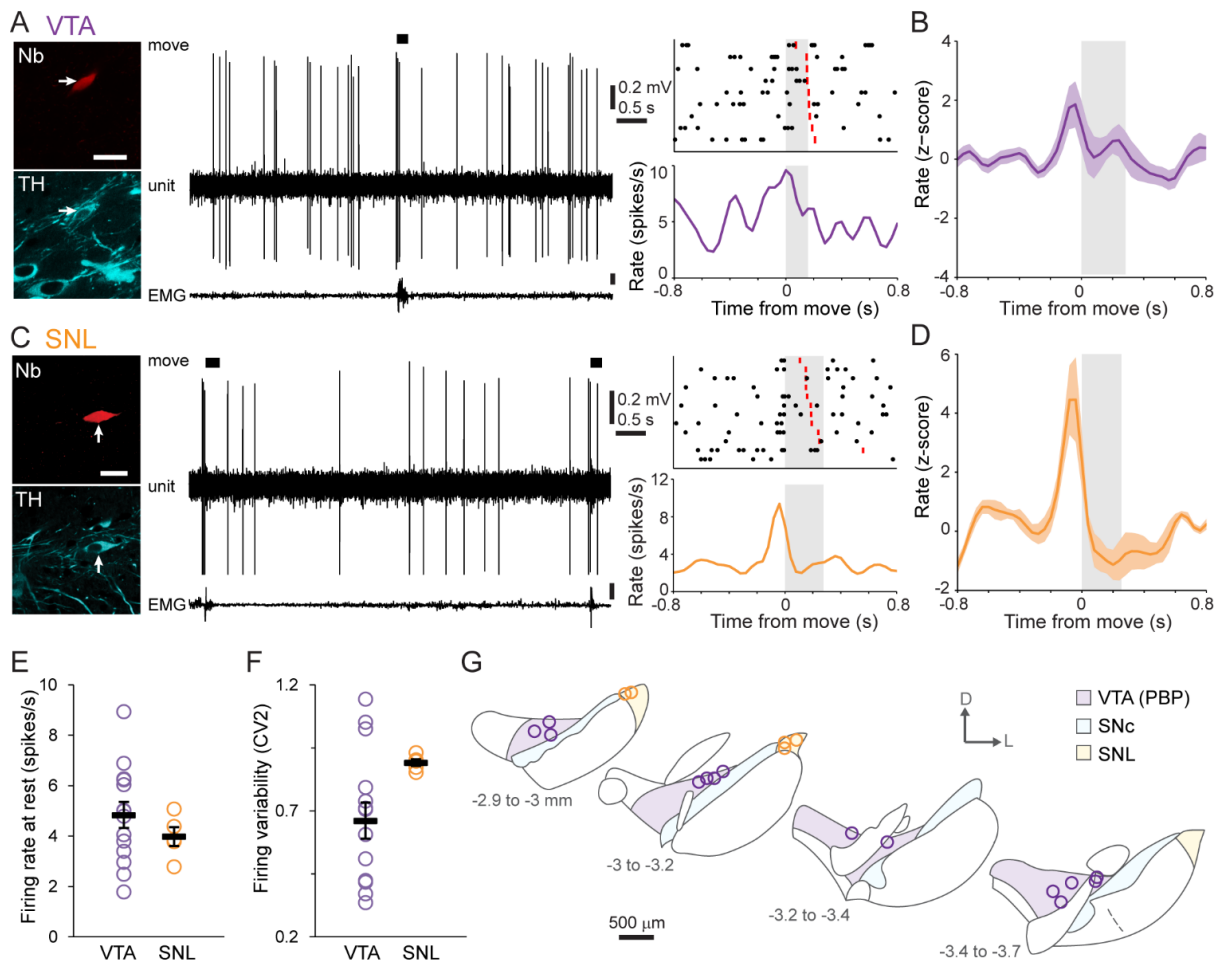


Fig. 2. Firing rate of VTA and SNL dopaminergic neurons does not change during movement onset. (A and C) Example single-unit activities and PETHs from identified dopaminergic neurons in the VTA (A) and SNL (C). (B and D) Mean normalized PETHs of all dopaminergic neurons in VTA (B) and SNL (D). On average, neurons transiently increased their firing rates just before movement but did not significantly change firing during the movement period itself (gray shading). (E and F) Mean firing rate (E) and regularity (F) of VTA and SNL dopaminergic neurons during alert rest ($n = 14$ VTA and 5 SNL neurons). (G) Schematic coronal sections denoting locations of all recorded and identified neurons in VTA (purple) or SNL (orange). Data are represented as mean \pm SEM. Scale bars in A and C insets, 20 μ m.

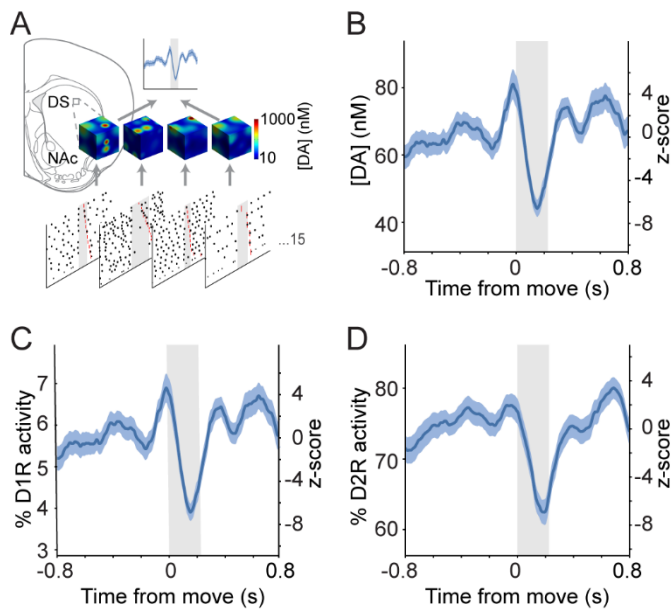


Fig. 3. Movement-related firing of SNc neurons significantly alters dopamine signaling in dorsal striatum. (A) Schematic of the computational model of dorsal striatal dopamine signaling. Dopamine release and receptor activity in a $\sim 25 \mu\text{m}^3$ cube of dorsal striatum (DS) was modeled using movement-related activity from each recorded SNc neuron ($n = 15$) as exemplified by snapshot concentration plots. Single-neuron responses were then averaged to generate population-level estimates of dopamine concentration. (B) Mean peri-movement dopamine concentrations. Note decrease in dopamine timed with movement onset. (C–D) Peri-movement activity profiles of low-affinity D1 dopamine receptors (C) and high-affinity D2 dopamine receptors (D). Mean response \pm SEM is plotted (left axis) and z-score (right axis). NAc, nucleus accumbens.

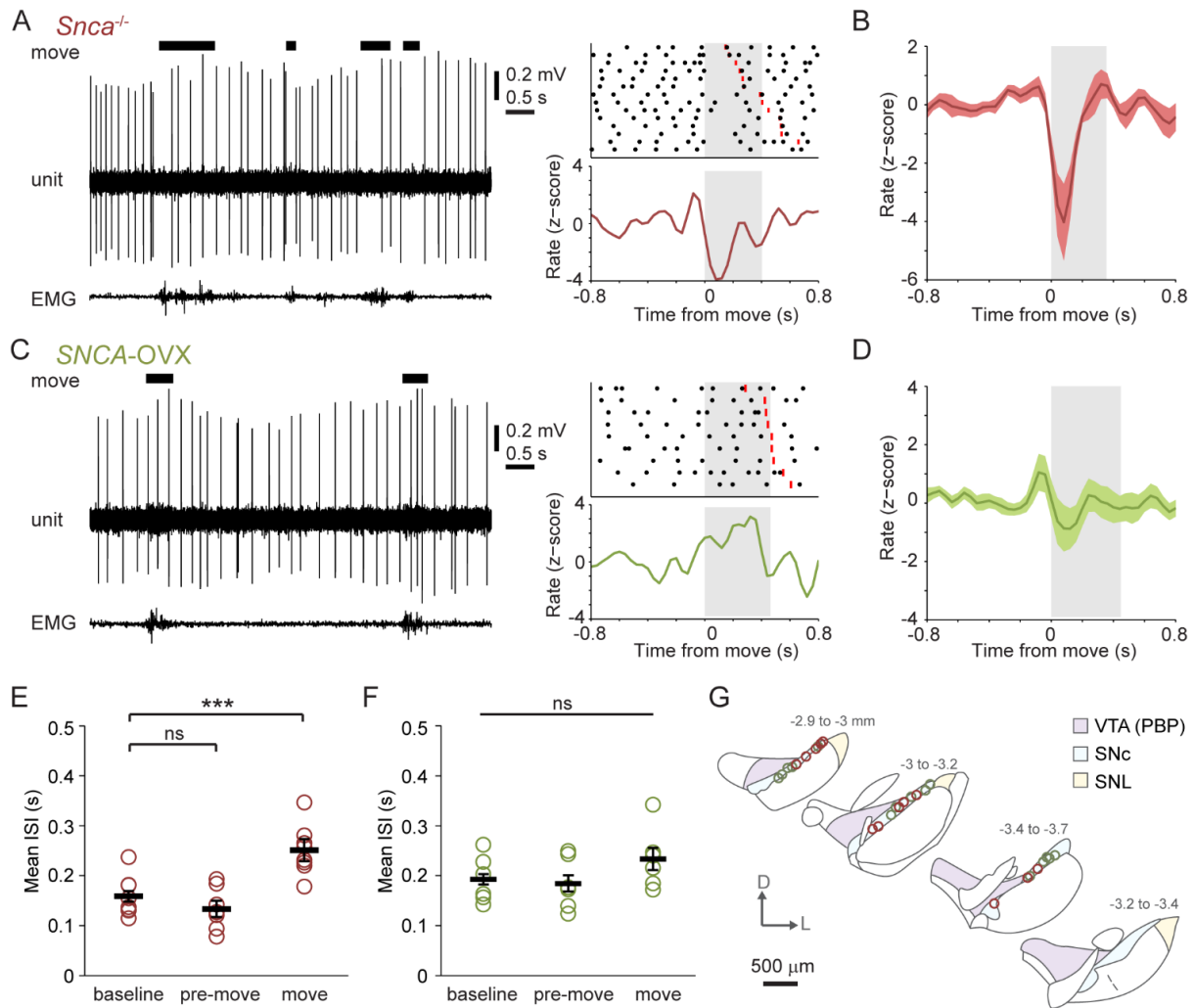


Fig. 4. Dopaminergic SNc neurons in parkinsonian mice do not reliably represent movement onset in their firing rates. (A and C) Example single-unit activities and PETHs from identified dopaminergic SNc neurons in 2 year-old *Snca*^{-/-} littermate controls (A) and *SNCA-OVX* parkinsonian mice (C). (B and D) Mean PETHs show that, on average, SNc neurons in *Snca*^{-/-} mice (n = 11 neurons) significantly decreased firing rate at movement onset (B) whereas those in *SNCA-OVX* mice (n = 12 neurons) show no significant change (D). (E) Mean interspike interval (ISI) of neurons in *Snca*^{-/-} mice during the baseline, pre-move and movement periods (defined as in Fig. 1); ISIs during movement were significantly longer than baseline (p < 0.001, n = 8 neurons, one way RM ANOVA with Dunnett's *post hoc*). (F) In *SNCA-OVX* parkinsonian mice, ISIs were not significantly different (p > 0.05, n = 6 neurons, one way RM ANOVA). (G) Schematic coronal sections denoting locations of recorded and

labeled neurons within the SNc (n = 13 (red) neurons from *Snca*^{-/-} and 14 (green) neurons from SNCA-OVX mice). Data are represented as mean ± SEM. *** p < 0.001; ns, not significant.

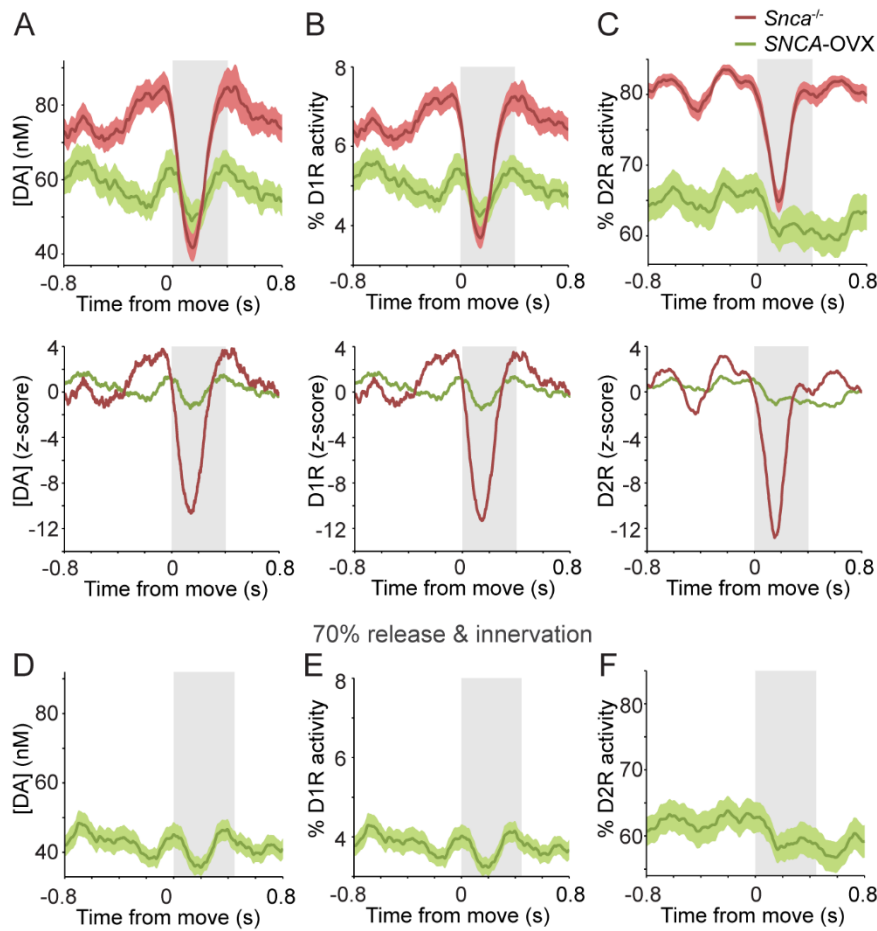


Fig. 5. Movement-related changes in striatal dopamine signaling are lost in parkinsonian mice. (A) Dorsal striatal dopamine concentrations (mean responses \pm SEM) simulated using movement-related activity from SNc neurons recorded in *Snca*^{-/-} littermate controls (red) or in parkinsonian SNCA-OVX mice (green) with corresponding z-scores. (B and C) Activity of low-affinity D1 receptors (B) and high-affinity D2 dopamine receptors (C). (D-F) Dopamine concentration (D), D1 receptor activity (E) and D2 receptor activity (F) modeled with parameters adjusted to match deficits present in aged SNCA-OVX mice (abnormally low firing rate of SNc neurons plus 30% reduction in dopamine release and dopaminergic innervation).