**Discussion**

The prevalence of disinhibitory circuit motifs in the brain and recent evidence for structured decision-related inhibitory activity argues for a more structured implementation of inhibition in computational models of decision-making. Here, we developed and characterized a dynamic circuit model of decision-making with dynamic local disinhibition. show the LDDM captures three important and characteristic features of decision-making – normalized value coding, WTA choice, and persistent activity – within a single circuit architecture. When fit to empirical behavioral observation, the LDDM accurately captures choice and RT patterns, driven by underlying model dynamics that reproduce the neural dynamics of empirical neurophysiological findings. Since the vast majority of empirical neural responses have been recorded from putative pyramidal neurons, we focus here on excitatory LDDM responses; however, the structured inhibition we model from newer anatomical data predicts input-selective inhibition. The model also makes novel predictions about inhibitory and disinhibitory activity dynamics and pharmacological manipulations that may warrant future examination. Furthermore, via disinhibitory control, the LDDM can exhibit both line attractor and point attractor forms of persistent activity without a change in the circuit structure. Finally, gated disinhibition in the LDDM provides a mechanism for top-down control of decision dynamics. Controlling the timing of disinhibition paces the decision process and replicates neural dynamics from various choice task variants.

Disinhibition has been previously linked in separate models to computational functions exhibited together by the LDDM. For example, (donut-like) The micro-circuit structure underlying donut-like inhibition has been revealed as a mechanism of localized disinhibition from the VIP neurons to the PV/SST neurons in the cortex (Karnani et al., 2016).Dendritic disinhibition can serve as a circuit mechanism for flexible information routing, gating on specific inputs to a circuit while gating off other pathways (Yang et al., 2016). Disinhibition in these models either plays the role as selective gain modulation or support competitive selection; however, with these structural elements isolated, these models are not able to capture the transition from value coding to WTA selection shown in the LDDM. In addition, PV neuron activation within a disinhibitory circuit motif can produce a divisive normalization of tuning curves in a model of visual cortex (Litwin-Kumar et al., 2016). This division can arise from different circuit mechanisms, such as reduced tuned input and firing rate nonlinearities. disinhibition has also been proposed to underlie the long timescales of information processing seen in working memory, as enhancing inhibitory-to-inhibitory connections stabilizes temporal dynamics and improves working memory performance in recurrent neural networks (R. Kim & Sejnowski, 2021). Taken together, these previous results and our current work reinforce the importance of incorporating disinhibition in circuit models of decision-making.

While absent in standard existing cortical decision models, disinhibition is a key element of action selection in models of the cortical-basal ganglia (CBG) system (Bogacz & Gurney, 2007; Frank, 2005; Lo & Wang, 2006; Schroll & Hamker, 2013; Wei et al., 2015). In the basal ganglia direct pathway, GABAergic neurons in the striatum inhibit neurons in the substantia nigra pars reticulata and internal globus pallidus, which in turn send inhibitory projections to the thalamus. Cortical inputs to the striatum thus produce a disinhibition of thalamic outputs to cortex and brainstem motor areas, resulting in motor facilitation. Crucially, the activation of disinhibition in the CBG is selective: the selection of a specific action requires a selective disinhibition driven by asymmetries in cortical inputs or striatal synaptic weights. This selective disinhibition is an essential element of computational models of the CBG system (Frank, 2005; Lo & Wang, 2006), including more complex models that incorporate global inhibition mediated by the indirect and hyper direct pathways (Bogacz & Gurney, 2007; Schroll & Hamker, 2013; Wei et al., 2015). While both the LDDM and the CBG models utilize disinhibition to drive selection, they differ in two important ways. First, disinhibition in the LDDM functions in a novel manner that implements a transition between value coding and WTA selection states. This transition is mediated by a broad/non-selectively activation of disinhibition across the decision circuits. The activation of disinhibition is not biased towards specific alternatives until a period of interaction with differential value inputs to option-specific subcircuits. Second, disinhibition in the LDDM is tightly integrated with the lateral inhibition that mediates competition between alternatives; consistent with the microarchitecture of cortex (Fu et al., 2014; Karnani et al., 2016; Kepecs & Fishell, 2014; Pi et al., 2013; S. Zhang et al., 2014), disinhibitory, inhibitory and excitatory neurons are part of the same local circuit. In contrast, the basal ganglia lacks local, lateral connections and mutual competition in the CBG models, which typically require both direct pathway disinhibition along with diffusive suppression of competing motor plans via the indirect or hyper direct pathways (Bogacz & Gurney, 2007; Schroll & Hamker, 2013; Wei et al., 2015). Thus, while conceptually similar to the CBG models, disinhibition in the LDDM is tightly integrated with competitive inhibition and provides a dynamic control of circuit state, both characteristics of decision-making in cortical brain areas.

The LDDM achieves the flexible reconfiguration of dynamical regimes from normalized value coding to WTA selection dynamics by a broad, initially non-selective disinhibition. Similar reconfiguration has been achieved by other circuit mechanisms. For example, a mutual inhibition network can capture the different regimes of sequential two-interval decision-making – stimulus loading, working memory, and comparison – by assuming a flexible reconfiguration of external inputs (Machens, 2005). Similar to the LDDM, this model can transit between point attractor (initial stimulus encoding), line attractor (working memory), and saddle point (comparison) dynamics, though it captures a sequential rather than a simultaneous decision process. Interestingly, disinhibition may also play a role in this model, providing a theoretical mechanism to switch the routing of external inputs within the circuit.

While normalized value coding and WTA selection have largely been modeled separately, the LDDM offers a biologically-plausible circuit architecture that integrates the two features. Existing neurophysiological evidence show that WTA dynamics and normalized coding co-exist in the same brain regions. On the one hand, neural activities show relative value coding in the early stage of decision-making, reflecting a context-dependent modulation consistent with the canonical divisive normalization computation (Churchland et al., 2008; Kira et al., 2015; Louie et al., 2011; Pastor-Bernier & Cisek, 2011; Rorie et al., 2010; Strait et al., 2014; Yamada et al., 2018). On the other hand, WTA choice dynamics are widely observed during decision making across multiple brain regions of non-human primates (Andersen & Buneo, 2002; Churchland et al., 2008; Ding & Gold, 2010, 2012, 2013; Dorris & Glimcher, 2004; Hanks et al., 2014; Kiani et al., 2008, 2014; J.-N. Kim & Shadlen, 1999; Louie & Glimcher, 2010; Padoa-Schioppa, 2013; Padoa-Schioppa & Conen, 2017; Pastor-Bernier & Cisek, 2011; Platt & Glimcher, 1999; Roesch & Olson, 2003; Roitman & Shadlen, 2002; Rorie et al., 2010; Shadlen & Newsome, 2001; Sugrue et al., 2004; Thura & Cisek, 2014, 2016, 2017; Yamada et al., 2018), including many of the brain regions that show normalized value coding. In addition, a transition from graded coding to WTA choice has been widely documented in the decision relevant regions mentioned above. Neural firing rates shows a graded coding of perceptual evidence and reward during the early stage of decision-making and gradually transition to a categorical coding for choice in the late period of decision-making (Churchland et al., 2008; Dorris & Glimcher, 2004; Gold & Shadlen, 2007; Platt & Glimcher, 1999; Roitman & Shadlen, 2002; Rorie et al., 2010; Shadlen & Newsome, 1996, 2001; Sugrue et al., 2004; B. Zhang et al., 2021). However, the evidence for one alternative is typically inversely related to the evidence for the other alternative, making it difficult to dissociate the dynamic effects of evidence integration and contextual information about other alternatives.

In the LDDM, disinhibition modulates the dynamics of the circuit without requiring changes in circuit structure. Existing models capture activity dynamics only in specific temporal intervals during decision-making tasks, or across trials in specific task paradigms (Hart & Huk, 2020; Hunt et al., 2012; Louie et al., 2014; Wang, 2002; Wong & Wang, 2006), and thus typically do not generalize across tasks. In contrast, gated disinhibition in the LDDM – driven by the external action instruction cue - controls the timing of valuation-to-WTA regime transition, enabling the LDDM to replicate neural dynamics in diverse task paradigms with different stimulus and action timing schedules (Kiani et al., 2008; Roitman & Shadlen, 2002; Rorie et al., 2010; Shadlen & Newsome, 2001). Recent research on neuromodulatory control of disinhibition offers biologically plausible mechanisms for such top-down control of circuit dynamics. In addition to evidence that VIP neurons are recruited by long-range projections from distanced regions (Lee et al., 2013; S. Zhang et al., 2014), VIP neurons are recruited by neuromodulatory projections such as acetylcholine (Fu et al., 2014) from the basal forebrain and pedunculopontine nuclei and serotonin from the red nucleus. With ionotropic acetylcholine receptor (nAChR) and serotonin receptors (5HT3aR and 5HT2R), VIP neurons depolarize to acetylcholine and serotonin (Alitto & Dan, 2013; Pfeffer et al., 2013; Rudy et al., 2011; Tremblay et al., 2016). The spiking mode of a major type of VIP neurons in layer II/III of the cortex switches from an input-insensitive burst-quiescent mode to an input-sensitive tonic mode under cholinergic and serotonin modulation (Prönneke et al., 2020). Such a mode-switching feature allows the disinhibitory neurons to receive excitatory projections with different gain under different level of neuromodulation, providing a mechanism to modulate network dynamics via disinhibition without a change in network structure*.* *In* *vivo* studies show that disinhibition mediated by cholinergic activation is triggered in a surprisingly fast time scale of tens of milliseconds (Alitto & Dan, 2013; Hangya et al., 2015; Letzkus et al., 2011), supporting a fast modulation mechanism of disinhibition and network plasticity.

An interesting feature of the LDDM is that it can produce both point attractor (Bathellier et al., 2012; Kopec et al., 2015; Niessing & Friedrich, 2010; Wills et al., 2005) and continuous/line attractor (Ganguli et al., 2008; Wimmer et al., 2014; Yoon et al., 2013) dynamics in persistent activity, a balance controlled by the level of disinhibition. Given ambiguous empirical evidence, it remains controversial whether persistent activity in neural circuits exhibit point attractor (Bathellier et al., 2012; Kopec et al., 2015; Niessing & Friedrich, 2010; Wills et al., 2005) or continuous/line attractor (Ganguli et al., 2008; Wimmer et al., 2014; Yoon et al., 2013) dynamics, and existing circuit models of persistent activity exclusively predict either a point attractor (Amit & Brunel, 1997; Brunel & Wang, 2001; Hopfield, 1982; Wang, 1999) or line attractor (Amari, 1977; Burak & Fiete, 2009; Compte, 2000; Ganguli et al., 2008; Seung, 1996). The LDDM can generate both line attractor and point attractor states, suggesting that attractor dynamics might not be a fixed property of a network; rather, it may be adaptive and controllable by a top-down signal operating via gated disinhibition.

In conclusion, here we introduce a novel, biologically-plausible architecture for decision-making based on local disinhibition, unifying the characteristic decision-making features of normalized value coding, WTA competition, and persistent activity into a single circuit. The LDDM captures psychometric and chronometric aspects of behavioral choice and predicts realistic neural dynamics in standard decision-making tasks. Local disinhibition provides a mechanism for top-down control of local decision circuit dynamics, enabling the LDDM to replicate variable task-dependent timing in diverse decision-making paradigms and implement speed-accuracy tradeoffs. These results suggest a new circuit mechanism for decision making, and emphasize the importance of incorporating interneuron diversity, local circuit architecture, and top-down control into models of the decision process.