**Flexible control of representational dynamics in a disinhibition-based model of decision making**

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**Abstract**

Inhibition is crucial for brain function, regulating network activity by balancing excitation and implementing gain control. Recent evidence suggests that beyond simply inhibiting excitatory activity, inhibitory neurons can also shape circuit function through disinhibition. While disinhibitory circuit motifs have been implicated in cognitive processes including learning, attentional selection, and input gating, the role of disinhibition is largely unexplored in the study of decision-making. Here, we show that disinhibition provides a simple circuit motif for fast, dynamic control of network state and function. This dynamic control allows a novel disinhibition-based decision model to reproduce both value normalization and winner-take-all dynamics, the two central features of neurobiological decision-making captured in separate existing models with distinct circuit motifs. In addition, the disinhibition model exhibits flexible attractor dynamics consistent with different forms of persistent activity seen in working memory. Fitting the model to empirical data shows it captures well both neurophysiological dynamics of value coding and psychometric choice behavior. Furthermore, the biological basis of disinhibition provides a simple mechanism for flexible top-down control of network states, enabling the circuit to capture diverse task-dependent neural dynamics. These results suggest a new biologically plausible mechanism for decision-making and emphasize the importance of local disinhibition in neural processing.

**Introduction**

Inhibition is an essential component in neural network models of decision-making. In standard decision models, pools of option-selective excitatory neurons compete in a winner-take-all selection process via feedback inhibition (Roach et al., 2023; X.-J. Wang, 2002; Wong & Wang, 2006). Generally, such inhibition is thought to be homogenous and non-selective, with a single pool of inhibitory neurons receiving broad excitation, and in turn inhibiting excitatory neurons. However, more recent findings suggest that inhibitory neurons interplay with the decision circuit in a more structured manner. At a functional level, inhibitory neurons exhibit choice-selective activity on par with excitatory neurons in frontal cortex (Allen et al., 2017), parietal cortex (Allen et al., 2017; Najafi et al., 2020), and striatum (Gage et al., 2010), i .At an anatomic level, interneurons exhibit a remarkable diversity in morphology, connectivity, and physiological functions (Kepecs & Fishell, 2014; Markram et al., 2004; Tremblay et al., 2016). A prominent circuit motif is local disinhibition, in which vasoactive intestinal peptide (VIP)-expressing interneurons inhibit the neighboring interneurons expressing somatostatin (SST) or parvalbumin (PV) that inhibit dendritic or perisomatic areas in pyramidal neurons, so that locally disinhibit the activities of the pyramidal neurons in the neighboring area (Chiu et al., 2013; Fino & Yuste, 2011; Fu et al., 2014; Karnani et al., 2014, 2016; Lee et al., 2013; Letzkus et al., 2011; Pfeffer et al., 2013; Pi et al., 2013; Urban-Ciecko & Barth, 2016) (**Fig. 2C**).

While disinhibitory circuit motifs have been implicated in cognitive processes including learning, attentional selection, and input gating (Fu et al., 2014; Letzkus et al., 2011; X.-J. Wang & Yang, 2018), how disinhibition functions in decision-making circuits is unknown. Local circuit inputs to the VIP neurons suggest that disinhibition may be a key mechanism for generating the mutual competition necessary for option selection in decision-making. In addition, given the existence of long-range inputs (Kepecs & Fishell, 2014; Lee et al., 2013; Pfeffer et al., 2013; Pi et al., 2013; Schuman et al., 2021) and neuromodulatory inputs (Alitto & Dan, 2013; Fu et al., 2014; Pfeffer et al., 2013; Prönneke et al., 2020; Rudy et al., 2011; Tremblay et al., 2016) to the VIP neurons, local disinhibition has been proposed to play a particular role in dynamic gating of circuit activity; such gating may be essential in decision circuits underlying flexible behavior, mediating top-down control of network function (Fu et al., 2014; Kamigaki, 2019; Lee et al., 2013; Letzkus et al., 2011; Pi et al., 2013; Schuman et al., 2021; S. Zhang et al., 2014). Here, we hypothesize that disinhibition controls a transition between information processing states, allowing a single decision-making circuit to both represent the values of alternatives and select between alternatives.

Value representation is prominent in the early stage of a decision, serving as integrated decision variables that combine outcome information such as expected gain and probability of realization. Neural firing rates in numerous decision-related brain areas vary with the integrated option values, including the frontal (Kiani et al., 2014; Kim & Shadlen, 1999; Padoa-Schioppa, 2013; Padoa-Schioppa & Conen, 2017; Pastor-Bernier & Cisek, 2011; Roesch & Olson, 2003; Thura & Cisek, 2014, 2016; Yamada et al., 2018) and parietal (Andersen & Buneo, 2002; Churchland et al., 2008; Dorris & Glimcher, 2004; Hanks et al., 2014; Kiani et al., 2008, 2014; Louie & Glimcher, 2010; Platt & Glimcher, 1999; Roitman & Shadlen, 2002; Rorie et al., 2010; Shadlen & Newsome, 2001; Sugrue et al., 2004) cortices and basal ganglia (Ding & Gold, 2010, 2012, 2013; Thura & Cisek, 2017). Recent research shows more specifically that neural value coding is contextual in nature, with the value of a given option represented relative to the value of available alternatives (Churchland et al., 2008; Kira et al., 2015; Louie et al., 2011, 2013, 2014; Pastor-Bernier & Cisek, 2011; Rorie et al., 2010; Strait et al., 2014; Yamada et al., 2018). Furthermore, this relative value coding employs divisive normalization (Hunt et al., 2012; Louie et al., 2011, 2015; Yamada et al., 2018), a canonical computation prevalent in sensory processing and thought to implement efficient coding principles (Carandini et al., 1999; Carandini & Heeger, 1994, 2012; Heeger, 1992, 1993; Schwartz & Simoncelli, 2001; Silver, 2010) and temporal adaptation(Chau et al., 2020; Heeger, 1992; Louie et al., 2013, 2015; Steverson et al., 2019; Webb et al., 2014).

Option selection and categorical choice occurs when the decision process progresses. A common and powerful neural mechanism for categorical choice is winner-take-all (WTA) competition (Wickens et al., 2007; Wilson, 2007). WTA dynamics are widely observed in multiple brain regions: the neural firing rate representing the chosen option or action target increases in concert with selection (often reaching a common activity threshold at choice), while firing rates representing the other unchosen option are suppressed (Churchland et al., 2008; Gold & Shadlen, 2007; Hanes & Schall, 1996; Hanks et al., 2014; Lo et al., 2015; Lo & Wang, 2006; Roitman & Shadlen, 2002; Rorie et al., 2010; Shadlen & Newsome, 2001; X.-J. Wang, 2002; Wong & Wang, 2006). The wide prevalence of WTA dynamics in decision-related neural activities suggests that it is a general feature of biological choice.

Computational decision models have identified core circuit motifs that produce either normalized value representation or WTA selection (**Fig. 1**). For normalized value representation, dynamic circuit-based models emphasize a crucial role for both lateral and feedback inhibition (LoFaro et al., 2014; Louie et al., 2014). In the dynamic normalization model (DNM), paired excitatory and inhibitory neurons represent each choice option (**Fig. 1A**); feedforward excitation gathers value inputs, lateral connectivity mediates contextual interactions, and feedback inhibition drives divisive scaling. This simple differential equation model emphasizes a crucial role of lateral connectivity and feedback inhibition in driving empirically-observed divisive scaling and contextual interactions (**Fig. 1B**).

For WTA selection, the predominant class of decision models (recurrent network models, hereafter RNM) propose a central role for recurrent connectivity (Houck & Person, 2014; Ito, 2002, 2006, 2008; Llinás, 1975; Sathyanesan et al., 2019; Sillitoe & Joyner, 2007) and non-selective feedback inhibition (Wickens et al., 2007; Wilson, 2007) (**Fig. 1C**). RNMs replicate psychophysical and neurophysiological results in perceptual (Furman & Wang, 2008; X.-J. Wang, 2002; Wong et al., 2007; Wong & Wang, 2006) and economic (Hunt et al., 2012; Jocham et al., 2012; Rustichini & Padoa-Schioppa, 2015; Soltani, 2006) choices, capturing the complex nonlinear dynamics of empirical neurons (**Fig. 1D**). Furthermore, the competitive nature of the RNM generates attractor states which maintain continued activity even in the absence of stimuli, consistent with persistent spiking activity associated with working memory during delay intervals (Brunel & Wang, 2001; Compte, 2000; Constantinidis et al., 2018; Furman & Wang, 2008; Hart & Huk, 2020; Lo & Wang, 2006; Macoveanu et al., 2006; Murray et al., 2017; Tegnér et al., 2002; M. Wang et al., 2013, p. 201; X.-J. Wang, 1999, 2002; Wong & Wang, 2006).

[Insert **Figure 1** about here]

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Despite electrophysiological evidence for coexisting relative value coding and WTA signals in prominent decision-related circuits, no current model integrates both properties within a single unified circuit. The current DNM cannot capture late-stage choice dynamics because it lacks a mechanism for WTA competition. Similarly, RNMs typically neither exhibit contextual value coding nor predict contextual choice patterns (X.-J. Wang, 2012), due to the lack of structured lateral inhibition. Here we propose that disinhibition is a biological plausible solution to unify these key features of decision-making into a single ciruit. We develop and characterize a novel biological circuit consisting of three neuronal types including local disinhibition. At its core, this model hybridizes the architectural features of divisive gain control and recurrent self-excitation used in existing models, but utilizes disinhibition rather than the commonly-assumed pooled inhibition to implement competition. We find that the disinhibition-based model unifies multiple characteristics of decision activity including normalized value coding, WTA choice, and working memory. Moreover, a top-down gating signal operating via this disinhibition enables the model to switch between the states of value representation and WTA selection, reproduce decision activity in a range of experimental paradigms with diverse task timing and activity dynamics. These findings suggest that local disinhibition provides a robust, biologically plausible integration of normalization and WTA selection in a single circuit architecture.