Convergent Circuit Computation for Categorization in the Brains of Primates and Songbirds

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Cold Spring Harbor Perspectives in Biology
www.cshperspectives.org

Categorization is crucial for behavioral flexibility because it enables animals to group stimuli into meaningful classes that can easily be generalized to new circumstances. A most abstract quantitative category is set size, the number of elements in a set. This review explores how categorical number representations are realized by the operations of excitatory and inhibitory neurons in associative telencephalic microcircuits in primates and songbirds. Despite the independent evolution of the primate prefrontal cortex and the avian nidopallium caudolaterale, the neuronal computations of these associative pallial circuits show surprising correspondence. Comparing cellular functions in distantly related taxa can inform about the evolutionary principles of circuit computations for cognition in distinctly but convergently realized brain structures.

A key aspect to intelligent behavior is the ability to group objects and events into meaningful categories. Categorization enables humans and animals to group stimuli into behaviorally relevant classes that can easily be generalized to new circumstances to provide behavioral flexibility (Miller et al. 2003; Seger and Miller 2010; Mansouri et al. 2020). Oftentimes the qualitative appearance of stimuli allows us to group objects into perceptual categories. For instance, when seeing four-legged carnivores, we group them into the categories "cats" and "dogs" based on bodily features. For other categories, we use quantitative information as grouping criteria. A most abstract quantitative category is set size, the number of elements in a set (Nieder 2020). When assessing set size, the numerosity of a set, the sensory appearance of the elements is meaningless. For example, three flowers, three sounds, and three grasps all belong to the category "three." Numbers are particularly fascinating categories because they can and need to be processed based on rules in working memory by animals (Cantlon and Brannon 2005; Bongard and Nieder 2010; Vallentin et al. 2012) or during symbolic mental calculation in humans (Dehaene et al. 1999; Nieder 2004; Kutter et al. 2018, 2022, 2023).

Over the past years, studies in nonhuman primates (i.e., macaques) and later in corvid songbirds (i.e., crows) have identified cellular mechanisms that give rise to the representation of numerical categories in these animals (for reviews, see Nieder 2016a,b, 2021a,b). A key finding is that single neurons in the associative neocortex of monkeys (Nieder et al. 2002, 2006; Sawamura et al. 2002; Nieder and Miller 2004; Okuyama et al. 2015; Ramirez-Cardenas et al. 2016) and the associative telencephalon of crows

Editors: Laura C. Andreae, Justus M. Kebschull, and Anthony M. Zador
Additional Perspectives on Evolution and Development of Neural Circuits available at www.cshperspectives.org

 doi: 10.1101/cshperspect.a041526
Cite this article as *Cold Spring Harb Perspect Biol* 2023;15:a041526

(Ditz and Nieder 2015; 2016; Wagener et al. 2018; Kirschhock et al. 2021; Kirschhock and Nieder 2022) responded selectively to a specific number of items. Such "number neurons" are tuned to preferred numerosities; they show a bell-shaped response curve as a function of the number of presented elements, with the preferred number at the center of this tuning curve. The sensory features of the elements have no effect on the neuronal activity of "number neurons," confirming that they represented abstract quantity categories (Nieder 2016a,b). This review demonstrates how neuronal number representations in the telencephalon provide a means to decipher exemplary microlevel circuit operations involved in cognitive functions.

Neural circuits implement the computations carried out by the brain (Dayan et al. 2011). In microcircuits, neuronal representations emerging from the activity of individual neuron types with specific patterns of synaptic connections are crucial (deCharms and Zador 2000). Such neuronal representations are typically depicted as tuning curves, the input–output (or "stimulus–response") functions of single neurons. The quality of a neuronal representation is mainly characterized by two features: the neuronal selectivity (the width of the tuning curve) to variations of stimulus parameters, and the neuronal discriminability (firing rate differences) between preferred and nonpreferred stimulus parameters. The crucial question addressed here is how high-quality neuronal representations to quantity categories are achieved by neurons forming microcircuits in the brain. Exploring this question in the telecephalic pallium of distantly related vertebrate groups—nonhuman primates and corvid songbirds (crows, ravens and jays)—can inform about the evolutionary principles of circuit computations for cognition in distinctly but convergently realized brain circuits (Fig. 1).

CIRCUITS AND COMPUTATIONS IN THE PRIMATE PREFRONTAL NEOCORTEX

Identifying Excitatory and Inhibitory Neurons

Improved perceptual discriminability of stimulus features is associated with more selective (i.e., narrower or sharper) tuning functions (Schoups et al. 2001; Yang and Maunsell 2004; Lee et al. 2012). Narrow numerosity tuning functions therefore allow a precise readout of the numerical values from neuronal responses. To sculpture tuning curves at the level of local microcircuits, inhibitory interneurons, which are outnumbered by excitatory neurons (mainly pyramidal projection neurons) by a ratio 4:1, play a crucial role (Markram et al. 2004; Wonders and Anderson 2006; Tremblay et al. 2016). By combining electrophysiological and anatomical methods, it has been shown that these two main cortical neuron types can be discriminated with sufficient precision in the primate prefrontal cortex (PFC) based on the waveforms of their action potentials (Fig. 2A–D; Merchant et al. 2012). Pyramidal cells tend to display relatively broad waveforms ("broad-spiking" neurons) and exhibit low firing rates ("regular-spiking" neurons) in extracellular PFC recordings of monkeys. In contrast, interneurons show narrow action potential waveforms ("narrow-spiking" neurons) and high firing rates ("fast-spiking" neurons) (Wilson et al. 1994; Rao et al. 1999; Constantinidis and Goldman-Rakic 2002; Johnston et al. 2009; Johnston and Everling 2009). In primate PFC, the broad waveforms of projection pyramidal neurons have been unequivocally identified based on antidromic stimulation (Johnston and Everling 2009). However, because these different classes of neurons are typically inferred from electrophysiological recordings in the absence of anatomical verification, they are addressed as "putative pyramidal cells" and "putative inhibitory interneurons."

We exploited these established differences between putative pyramidal cells and inhibitory interneurons while recording extracellularly in the PFC and interparietal sulcus (IPS) of macaques trained to discriminate numerical quantity (Diester and Nieder 2008). Using spike sorting techniques, we isolated different neurons based on their distinct action potential waveforms and assigned them based on statistics to the two (excitatory and inhibitory) neuron classes (Fig. 2A–D). This allowed us to gain insight into the functional roles these two classes of neurons assume in local microcircuits during number processing.

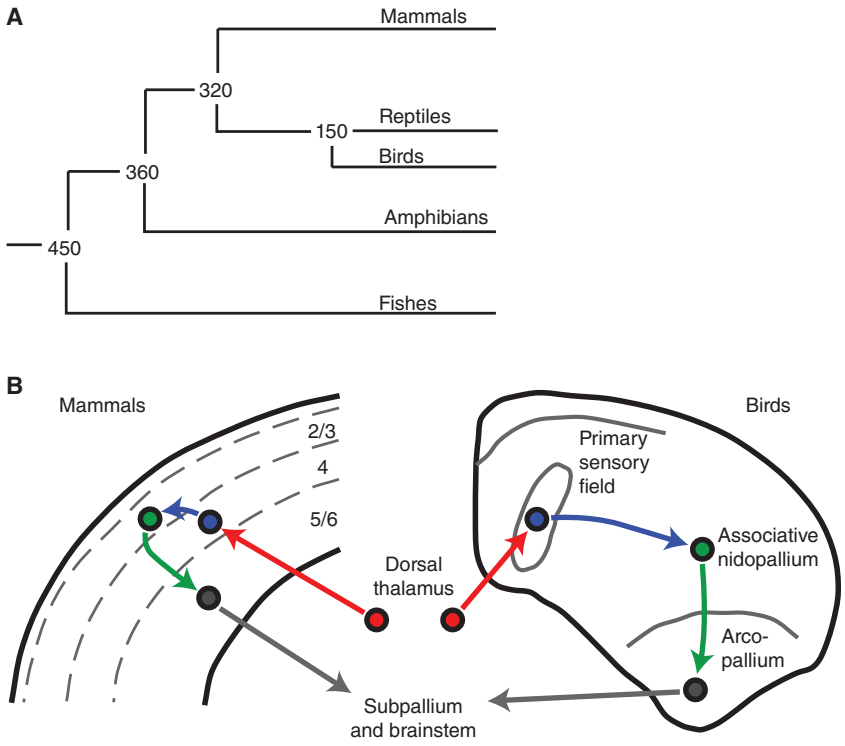

Figure 1. Phylogenetic modifications of major pallial circuits. (*A*) Phylogenetic relationship and divergence times (millions of years ago) of vertebrate taxa. Branch lengths are not proportional to time. (Panel *A* is based on data in Hedges 2002 and Striedter and Northcutt 2020.) (*B*) Cell-type homology hypothesis (Karten 1969) for input and output neurons of mammalian and avian pallium. (*Left*) In mammals, input from the dorsal thalamus (red) terminates on neurons in layer 4 (blue) of the neocortex. These neurons project to layers 2/3 neurons (green), which in turn connect with layer 5/6 pyramidal neurons (gray). These neurons send axons to subcortical regions. (*Right*) An equivalent circuit is present in the avian pallium. Here, input from the dorsal thalamus (red) terminates in primary sensory nuclei (such as the primary auditory field L) (blue). These neurons connect (likely via mediatory interneurons) to interneurons in associative nidopallial regions (green), which in turn project to output arcopallial regions (gray) that constitute the source of pallial output to subpallial regions. (Panel *B* created from data in Dugas-Ford et al. 2012, Dugas-Ford and Ragsdale 2015, and Striedter and Northcutt 2020.)

Response Characteristics of Putative Pyramidal Cells and Interneurons in PFC to Categories

In PFC, putative pyramidal cells and inhibitory interneurons were tuned to numerical categories according to the anatomically expected proportions (Diester and Nieder 2008). Compared to putative pyramidal cells, putative interneurons generally responded with higher firing rates and showed stronger stimulus-evoked responses. Both cell types showed interesting temporal and selectivity differences in numerosity tuning.

With respect to time, putative interneurons responded (by 46 msec) faster to visual stimulation and also discriminated numerical categories (by 51 msec) earlier than putative pyramidal cells. This faster time course could support a role of interneurons in feedforward inhibition of pyramidal cells. Faster response characteristics can be explained by significantly larger and faster excitatory postsynaptic potentials (EPSPs) of fast spiking interneurons compared to pyramidal cells (Povysheva et al. 2006), which in turn can cause lower thresholds for action potential gen-

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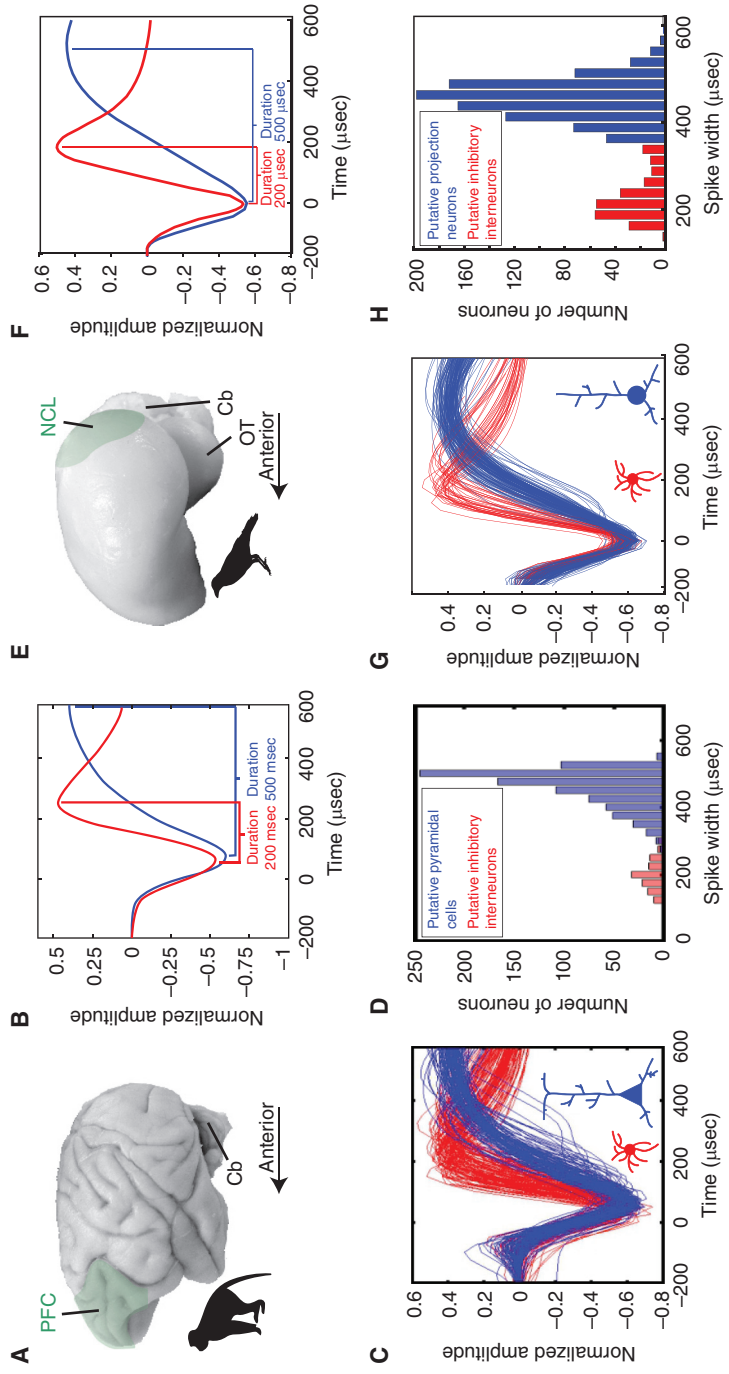

Figure 2. *(See following page for legend.)*

Cite this article as *Cold Spring Harb Perspect Biol* 2023;15:a041526

eration and thus shorter latencies for EPSP–spike coupling in interneurons.

In addition to temporal differences, the two cell types differed in neuronal selectivity to quantity categories. Putative inhibitory interneurons exhibited much broader tuning curves than putative pyramidal cells (Diester and Nieder 2008). This finding is interesting because inhibition by broadly tuned inhibitory interneurons could increase the selectivity of pyramidal cells by sharpening their tuning to preferred categories (Wang et al. 2004). As a consequence of sharper tuning, putative pyramidal cells were more strongly modulated by numerosity (i.e., higher ratio of firing rates elicited by the most- and least-preferred numerosity). However, putative inhibitory interneurons discriminated quantity categories more accurately, or reliably, compared to putative pyramidal cells (as measured by the area under the receiver operating characteristic curve) (Diester and Nieder 2008). The higher reliability of putative inhibitory interneurons could be explained by their lower membrane threshold rendering them more likely to fire in response to an input (Povysheva et al. 2006).

It is worth mentioning that the basic circuitries enabling categorical number representations seem to be hard-wired because numerosity tuning exists even in numerically naive animals that have never been trained to discriminate numerosity (Viswanathan and Nieder 2013; Wagener et al. 2018; Kobylkov et al. 2022a). At the same time, numerosity tuning of neurons can be shaped and sharpened through experience and attention (Viswanathan and Nieder 2015). More specifically, putative pyramidal cells show higher numerosity selectivity in discriminating monkeys, which suggests a preferential role of these projection neurons in active (explicit) numerosity processing. This was seen when we compared numerosity tuning selectivity of neurons in monkeys that performed an implicit numerosity task in which only the color of the dots in a set was behaviorally relevant with the situation in an explicit numerosity task in which the monkeys discriminated the number of dots in a set (Viswanathan and Nieder 2015). Indeed, when the same monkeys were retrained from an implicit numerosity task (discriminate only the color of dots) to perform an explicit numerosity task (discriminate the number of dots), PFC neurons became more selective to numerosity during active numerosity discrimination (Viswanathan and Nieder 2015). This improvement in numerosity coding was exclusively due to putative pyramidal neurons; putative inhibitory interneurons were unaffected by behavioral relevance. This effect was specific for the PFC as neither cell class in simultaneously recorded ventral intraparietal area (VIP) of the parietal lobe showed a corresponding effect (Viswanathan and Nieder 2015).

Beyond representing categories, putative pyramidal cells in PFC also seem to contribute to other explicit tasks, such as learning to memorize stimuli (Qi et al. 2011), judging a specific visual parameter (Hussar and Pasternak 2009),

Figure 2. Characterizing putative pyramidal cells and inhibitory interneurons from extracellular recordings in monkey prefrontal cortex (PFC) (*A–D*) and crow nidopallium caudolaterale (NCL) (*E–H*). (*A*) Lateral view of a macaque monkey brain depicting the dorsolateral PFC. (*B*) The width of an action potential waveform is defined as the time elapsed between the spike trough and the peak. Two mean waveforms show the spiking difference between putative inhibitory interneurons (red) and putative pyramidal cells (blue). (*C*) Normalized average waveforms of a random subset of extracellularly recorded PFC neurons aligned by their minimum. Waveforms of putative inhibitory neurons (narrow spiking neurons) are depicted in red; waveforms of putative pyramidal cells (broad spiking neurons) are depicted in blue. (*D*) Bimodal distribution of waveform widths shown in *C* indicating the two major cell-type classes in PFC. (*E*) Lateral view of a crow brain depicting the NCL. (*F*) Action potential waveform characterization for NCL neurons. Same layout as in *B*. (*G*) Normalized average waveforms of a random subset of extracellularly recorded NCL neurons aligned by their minimum. Same layout as in *C*. (*H*) Bimodal distribution of waveform widths shown in *G* indicating the two major cell-type classes in NCL. Same layout as in *D*. (Cb) Cerebellum, (OT) optic tectum. (Panels *B–D* are adapted from Diester and Nieder 2008 with permission from the Society for Neuroscience © 2008. *F–H* adapted from Ditz et al. 2022 under a Creative Commons Attribution 4.0 International License.)

and making decisions (Ding and Gold 2012). Thus, neuronal coding improvements accompanying behavioral relevance seem to result from selectivity increases in putative pyramidal cells of the PFC. Given that PFC projection neurons project in a feedforward manner to premotor output structures, this enhanced coding could well be translated into behavioral precision (Gerbella et al. 2010; Borra et al. 2017; Battaglia-Mayer and Caminiti 2019). Alternatively, or in addition, feedback from PFC projection neurons to upstream areas could enhance cognitive control by influencing sensory areas (Gregoriou et al. 2014; Bichot et al. 2019).

Circuit Interactions between Functionally Coupled Category-Selective Pyramidal Cells and Interneurons

If adjacent putative inhibitory interneurons and pyramidal cells constitute elements of microcircuits interacting with inhibition and excitation, their category tuning profiles are expected to differ or even be inverted relative to each other. To test this, we investigated the tuning of single cells recorded simultaneously at the same electrode. Spike sorting (i.e., the assignment of different neurons based on their distinct action potential waveforms) enabled us to isolate more than one neuron that has been recorded at the same electrode tip and therefore in an immediate anatomical vicinity (Diester and Nieder 2008). Such juxtaposed neurons suggestive of microcircuit membership may interact more frequently than neurons recorded at different sites.

Indeed, inverted tuning to quantity categories between adjacent putative inhibitory interneurons and pyramidal cell pairs recorded at the same electrode tip in PFC was found (Diester and Nieder 2008). This inverse tuning between putative inhibitory interneurons and pyramidal cells occurred significantly more often compared to cell pairs consisting of neighboring putative pyramidal cells. This result, together with the finding that putative inhibitory interneurons showed shorter latencies, again suggests that inhibitory interneurons may exert feedforward inhibition on pyramidal cells. This notion also fits with the finding that putative inhibitory interneurons in PFC show larger receptive fields compared to pyramidal cells (Viswanathan and Nieder 2017a,b), potentially enabling inhibitory neurons to exert spatially broad lateral inhibition on pyramidal cells. This, in turn, may support PFC neurons' global and spatially released number representations beyond the neurons' classical receptive fields (Viswanathan and Nieder 2020).

More direct evidence for circuit interactions came from PFC neuron pairs for which functional connectivity could be established (Fig. 3A,B). One way of revealing functional coupling between neurons is the demonstration of temporally correlated discharges (Epping and Eggermont 1987; Barthó et al. 2004). Cell pairs consisting of putative pyramidal cells showed tuning to similar preferred numerosities and were mainly excited in synchrony (Fig. 3B); inhibitory effects between neighboring putative pyramidal cells were largely absent. These findings likely reflect shared excitatory input on putative pyramidal cells (Rao et al. 1999). In contrast, neuron pairs consisting of a putative inhibitory interneuron and a pyramidal cell were functionally connected via a negative correlation of temporal firing and showed inverted tuning relative to each other; in other words, if a putative inhibitory interneuron fired, the functionally connected pyramidal cell was significantly inhibited, and vice versa (Fig. 3A).

Our results during abstract categorization mirrored earlier findings showing that neighboring putative inhibitory interneurons and pyramidal cells in primate PFC exhibit opposite response properties in the spatial domain. In earlier studies, inverted spatial direction selectivity of nearby putative inhibitory interneurons and pyramidal cells was observed (Wilson et al. 1994; Constantinidis and Goldman-Rakic 2002; but see Rao et al. 1999 for contrasting results). Interestingly, blockade of GABAergic inhibition led to broadening of PFC neurons' spatial tuning profiles. This is in agreement with a role of inhibition in shaping neuronal tuning (Rao et al. 2000).

Mechanistically, these findings indicate that inhibitory interneurons systematically exert inhibition on numerosity-tuned pyramidal cells, a mechanism also proposed by recurrent network models for neuronal tuning in the service of spa-

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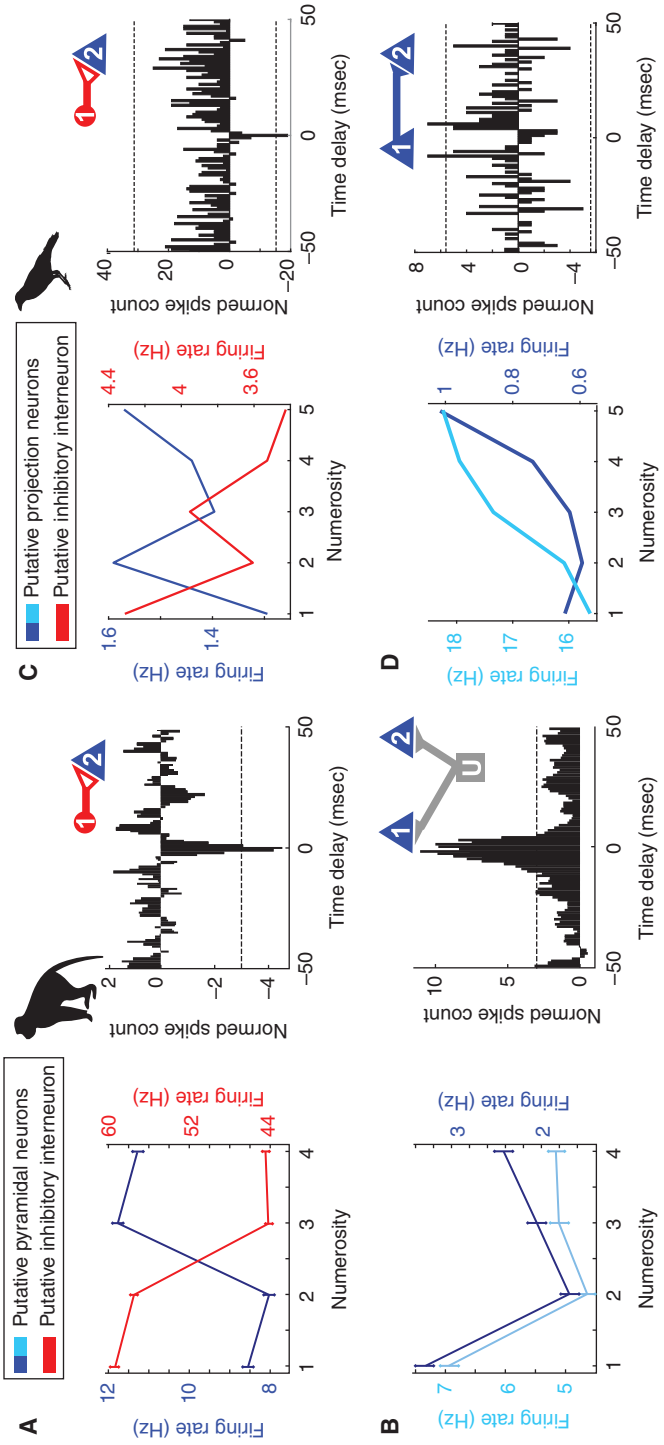

Figure 3. (*See following page for legend.*)

tial working memory (Compte et al. 2000). Within this framework, the preferred numerosities of the inhibitory interneurons represent the nonpreferred numerosities at the flanks of a pyramidal cell's numerosity tuning function. The tuning curve shoulders of the pyramidal cell are lowered by this lateral inhibition, which thereby sharpens the pyramidal cell's tuning curve. Lateral inhibition may also explain the more precise tuning of neurons in the subitizing range below number 5 in the human medial temporal lobe (Kutter et al. 2023).

Interestingly, microcircuit operations are not identical across neocortical brain regions. A direct comparison of functional connectivity patterns of adjacent cortical cell types in PFC versus IPS resulted in marked differences (Viswanathan and Nieder 2017a,b). Relative to IPS, more inhibitory and temporally more precise connections exist in PFC. The functional connectivity patterns observed in IPS are more reminiscent of early visual areas, whereas prefrontal local circuits seem to have developed differently. Perhaps inhibition figures more prominently in PFC to suppress prepotent behavioral output and to shape behaviorally relevant representations.

A defining feature of the PFC is its support of working memory functions (Miller 2013; Miller et al. 2018). An extension of the mechanism depicted above may explain how numerosity selective activity could persist into delay periods to support tuning to categories during working memory. After a quantity category has been encoded during presentation of a display, an ensemble of pyramidal cells exhibits tuned sustained activity through recurrent excitations based on positive feedback loops of activity between excitatory pyramidal cells (Wang 1999, 2001). These tuned pyramidal cells activate local inhibitory interneurons, which, in turn, inhibit pyramidal cells with a different numerosity preference. Remarkably, such a reverberatory mechanism could persist after a stimulus has ceased into delay periods to support neuronal tuning to categories during working memory (Durstewitz et al. 2000).

Prefrontal Neuron Classes Are Differentially Affected by Dopamine Receptors

Neuronal microcircuits in PFC process cognitive information not in a static environment but are influenced by neuromodulators such as dopamine (Ott and Nieder 2019). Two main dopamine receptor families, D1R (subtypes D_1 and D_5) and D2R (subtypes D_2, D_3, and D_4), mediate dopamine's control of neuronal activity, and both are expressed in both excitatory pyramidal cells and inhibitory interneurons (Smiley et al. 1994; Mrzljak et al. 1996; Muly et al. 1998; Gao and Goldman-Rakic 2003; de Almeida and Mengod 2010; Santana and Artigas 2017). To test the causal impact of dopamine receptor activation

Figure 3. Tuning behavior of functionally connected pairs of numerosity-selective neurons recorded in monkey prefrontal cortex (PFC) (*A*,*B*) and crow nidopallium caudolaterale (NCL) (*C*,*D*). (*A*) (*Left* panel) Numerosity tuning curves of a pair of coupled PFC neurons consisting of tuned putative pyramidal cell and inhibitory interneuron. (*Right* panel) Corresponding spiking cross-correlogram (shift-corrected and baseline-subtracted; dotted lines indicate positive and negative significance thresholds, respectively) with a significant negative trough around time delay 0 msec indicating forward inhibition. *Inset* shows putative connectivity between inhibitory neuron (red) and excitatory neuron (blue). Open triangles indicate inhibitory synapse. (*B*) Same layout as in *A*, but for a pair of coupled putative pyramidal cells from monkey PFC. Both neurons exhibit equivalent numerosity tuning profiles while showing a positive peak around time delay 0 msec in the cross correlogram indicating shared excitation (from an unknown input neuron, *U*). *Inset* shows putative connectivity between the two excitatory neurons (blue). Closed triangles indicate excitatory synapses. (*C*) Numerosity tuning curves and cross correlograms of a crow NCL cell pair consisting of a putative projection neuron and an inhibitory interneuron with inverse tuning profiles that are functionally coupled. Same layout as in *A*. (*D*) Numerosity tuning curves and cross-correlograms of a crow NCL cell pair consisting of two coupled putative projection neurons Same layout as in *B*. *Inset* shows putative unidirectional excitatory input from one excitatory neuron to the other (blue). (Panels *A* and *B* are adapted from Diester and Nieder 2008 with permission from the Society for Neuroscience © 2008. *C* and *D* adapted from Ditz et al. 2022 under a Creative Commons Attribution 4.0 International License.)

on neuronal tuning, we used a combination of single-neuron recordings and simultaneous pharmacological stimulation of dopamine receptor families via micro-iontophoretic drug applications (Jacob et al. 2013; Stalter et al. 2020). The two dopamine receptor families had strong but differential impact on how the neurons represented the encoding and rule-based memorization of numerical categories (Ott et al. 2014; Ott and Nieder 2017).

In monkeys performing a delayed match-to-numerosity task with a distractor in the working memory period (Jacob and Nieder 2014), we found a cell-type-specific influence of D1Rs on the coding quality of the sample numerosity in the working memory period after a distracting numerosity had been shown: in putative pyramidal neurons, D1R inhibition improved neuronal coding quality after the interference, whereas D1R stimulation weakened it. However, the inverse pattern was observed in putative interneurons (Jacob et al. 2016). These results imply that dopaminergic neuromodulation of PFC circuits and their cell types via D1R regulates representations of behaviorally relevant categories that compete with task-irrelevant categories. The results emphasize the different roles of different cell types in working memory coding and highlight the need to consider cortical cell types.

CIRCUITS AND COMPUTATIONS IN THE SONGBIRD NIDOPALLIUM

Circuit Components in the Avian Pallium

Compared to mammals, the microcircuits in the avian telencephalon are significantly less well explored, despite some birds exhibiting sophisticated categorization capabilities (Soto and Wasserman 2014; Scarf et al. 2016; Huber and Aust 2017; Pusch et al. 2023). This lapse also has to do with a century-old misunderstanding concerning the building plan of the telencephala of sauropsids (i.e., reptiles and birds). The understanding of the avian telencephalon was revolutionized when new phylogenetic and developmental neuroanatomical studies convincingly demonstrated that the avian pallium, despite its structural independencies that emerged in evolutionary time, is homologous to that of mammals and similarly dominates the telencephalon (Jarvis et al. 2005). Unravelling the functional-level convergence between neuronal operations in nonhuman primates and corvid songbirds will permit a deeper understanding of evolutionarily superior circuit computations that are realized in independently evolved brains.

Birds are vertebrates that possess an alternative telencephalic layout compared to mammals. Most remarkable, the avian telencephalon lacks a layered cerebral cortex. Since birds and mammals diverged from a last common stem-amniote 320 million years ago (Fig. 1A; Hedges 2002), they evolved a profoundly distinct cellular arrangement as integrative structures from different territories of the embryonic pallium. Of the four original pallial territories (ventral, lateral, dorsal, and medial), birds evolved rather nuclear integration centers out of the ventral pallium, whereas the major integration center of mammals, the six-layered neocortex, develops from the embryonic dorsal pallium (Jarvis et al. 2005; Puelles 2017; Cárdenas and Borrell 2020; Striedter and Northcutt 2020; Nieder 2021b).

Despite these differences in structural origins, the avian ventral pallium (of which the dorsal ventricular ridge [DVR] emerges) and the mammalian neocortex converged on comparable circuit operations (Fig. 1B). The layered neocortex exhibits three circuit building blocks (Shepherd 2009). First, input neurons that receive sensory information relayed by the thalamus enter the thalamo-recipient. Second, intracortical neurons process this information locally in projecting layers 2 and 3. Third, output neurons in the subcortically projecting layers 5 and 6 project to subcortical motor control centers. Remarkably, these circuit building blocks can all be identified in the avian pallium. Columnar organizations and layering may even occur in sensory pallial areas of the bird brain (Wang et al. 2010; Ahumada-Galleguillos et al. 2015; Stacho et al. 2020; Fernández et al. 2021). Beyond sensory pallial areas, however, these circuit components are arranged along a sequence of nuclei rather than layers.

The three major circuit components of the neocortex can be retraced in the bird pallium

(Fig. 1B; Karten 1969, 2013; Reiner 2013). Recent molecular studies show that markers of mammalian cortical layer 4 neurons are expressed by neurons in the major thalamo-recipient nuclei of chicken telencephalon (Dugas-Ford et al. 2012; Dugas-Ford and Ragsdale 2015). Moreover, neurons of the avian mesopallium, an associative avian brain region, have the connectivity of cortical layers 2/3 neurons and express several genes that uniquely mark layers 2/3 in mammals (Suzuki et al. 2012). In mammals, neurons of cortical layers 2/3 receive input from layer 4 thalamo-recipient neurons and project to layer 5 output neurons (Shepherd 2009; Harris and Shepherd 2015). Indeed, different layer 5 markers are expressed in avian pallial structures, such as the arcopallium, that provide telencephalic output projections to the brainstem. From an evolutionary point of view, the three main types of pallial neurons (thalamo-recipient, intrapallially projecting, and extra-telencephalically projecting neurons) likely represent three ancient neuron types found in the common ancestor stem amniote pallium. From these neuron types, comparable circuits seem to be built in their descendants (mammals and birds, respectively), independent of whether they were arranged in a nuclear or laminar fashion (Reiner 2013).

On a more fine-grained level, microcircuits both in the mammalian neocortex and the avian pallium are composed of glutamatergic excitatory projection neurons and GABA (γ-aminobutyric acid)-ergic local inhibitory interneurons (Spool et al. 2021). These major cell types were molecularly identified in the avian brain using promoter-specific viral optogenetics (Spool et al. 2021). These authors explored the molecular phenotypes of mammalian neocortical excitatory (via calmodulin-dependent kinase α [CaMKIIα] promoters) and inhibitory neurons (via glutamate decarboxylase 1 [GAD1] promoters) (Lee et al. 2012; Pfeffer et al. 2013) in the nidopallium of zebra finches. They found that promoter-driven molecular cell identity segregated nidopallial neurons with distinct physiological properties, such as the known spike waveform differences, into excitatory and inhibitory cell types as it does in mammalian pallium (Spool et al. 2021).

Importantly, however, avian pallial circuits engage genetically separate classes of excitatory and inhibitory neurons that are not present in the mammalian neocortex. Colquitt et al. (2021) showed that excitatory (glutamatergic) neurons have transcription factor profiles similar to the mammalian ventral pallium but not to the neocortex, which develops from the dorsal pallium (Colquitt et al. 2021). In addition, and consistent with the assumption that avian nido-/arcopallial regions are of ventral pallial origins, the most abundant inhibitory (GABA-releasing) neuron type in these avian brain regions resembles inhibitory neurons in mammalian ventral pallial derivatives but is absent from the neocortex (Colquitt et al. 2021). Thus, the songbird nidopallium and the mammalian neocortex contain transcriptionally relatively similar neurons, which, however, have distinct developmental origins.

The Avian Pallial Association Area Nidopallium Caudolaterale

In birds, a highly associative pallial brain area termed "nidopallium caudolaterale (NCL)" was identified as an essential cognitive brain area giving rise to complex avian cognition (Güntürkün 2005; Nieder 2017a,b; Nieder et al. 2020). The NCL is certainly not homologous to the mammalian PFC but it is often called a functional equivalent of the PFC. Recordings in behaving crows showed NCL neurons that represent stimulus association (Moll and Nieder 2015; Veit et al. 2015), encode working memory information (Veit et al. 2014; Rinnert et al. 2019), signify motor plans (Rinnert and Nieder 2021), and are engaged in abstract magnitude categorization (Wagener and Nieder 2023). Like monkey PFC and IPS neurons, NCL neurons in crows are also tuned to numerosity (Ditz and Nieder 2015, 2016, 2020; Wagener et al. 2018; Kirschhock et al. 2021; Kirschhock and Nieder 2022). Thus, both primates and corvids convergently evolved pallial structures that generate executive processes.

The similarities between the NCL and the PFC even extend to the neuromodulator dopamine. In fact, the anatomical delineation of the NCL in the avian telencephalon is based on the criterion of a strong dopaminergic innervation

arising from the midbrain (Divac et al. 1985; Waldmann and Güntürkün 1993; Wynne and Güntürkün 1995; von Eugen et al. 2020; Kersten et al. 2022; Kobylkov et al. 2022b). Similar to the primate PFC, the avian NCL also contains D1Rs and D2Rs that play a functional role in cognition (Dietl and Palacios 1988; Durstewitz et al. 1998). Dopamine concentration in pigeon NCL (measured via microdialysis) increased during a working memory task compared to the same task without a memory delay (Karakuyu et al. 2007). Stimulation of D1R in NCL (and striatum) improved performance on working memory tasks (Herold et al. 2008), whereas blockade of D1R in NCL of pigeons resulted in severe disruptions of discrimination reversal learning (Diekamp et al. 2000). Currently, the influence of the neurotransmitter dopamine on single neurons and microcircuits in the avian pallium is unknown. However, in light of these findings in cognitive tasks and given that D1R manipulation in the auditory nidopallium changes the songbirds' behavioral song preference (Barr et al. 2021), dopamine most likely has an impact on the categorical tuning properties of neurons.

Contributions of Inhibitory and Excitatory Neurons in the Avian Nidopallium Caudolaterale in Abstract Categorization

How tuning functions to abstract categories are shaped by neuronal circuit computations in the avian pallium remained elusive until recently. Applying the same methods as for extracellular PFC recordings, we demonstrated that local microcircuits containing excitatory projection neurons and inhibitory interneurons play a key role in sculpturing tuning functions (Fig. 2E,F; Ditz et al. 2022). As crucial circuit components, these major neuron types exist in song-related pallial brain areas of songbirds (Spiro et al. 1999; Calabrese and Woolley 2015; Kosche et al. 2015; Yanagihara and Yazaki-Sugiyama 2016; Bottjer et al. 2019). As outlined above, these major cell type classes and their physiological characteristics were molecularly identified in the bird brain (Spool et al. 2021), supporting earlier studies reporting network computations via "putative" excitatory and inhibitory cell types segregated based on extracellular waveform separation.

In the NCL of crows discriminating numerosities, recorded neurons can also be classified into broad-spiking putative projection neurons and narrow-spiking putative inhibitory interneurons based on their action potential profile (Ditz et al. 2022). These avian neuron classes show the same characteristics as those in the primate PFC. First, the cellular proportion of roughly 80% projection neurons and 20% interneurons corresponded to cell counts reported in the avian (Yanagihara and Yazaki-Sugiyama 2016; Bottjer et al. 2019; Ditz et al. 2022) and mammal brains (Markram et al. 2004). Second, putative NCL interneurons showed higher firing rates compared to putative projection neurons, confirming earlier findings in the auditory/song system (Schneider and Woolley 2013; Yanagihara and Yazaki-Sugiyama 2016). Third, stimulus-evoked responses were greater in putative NCL interneurons compared to projection neurons. Fourth, putative NCL interneurons responded significantly faster to the onset of stimuli (Ditz et al. 2022).

Because the distinct physiological properties of putative inhibitory interneurons and projection neurons were suggestive of them having different functions in neuronal circuits, we probed these NCL neuron types' contributions in quantity categorization. To that aim, we used the same delayed-match-to-numerosity task in crows as previously described for monkeys. Surprisingly, the results were virtually identical to those earlier obtained for the PFC of primates (Diester and Nieder 2008). Of those NCL neurons that were tuned to preferred numerosities, putative projection neurons show a sharper and more selective tuning than putative inhibitory interneurons (Ditz et al. 2022). In addition, neighboring putative projection neurons recorded at the same electrode tip exhibited comparable numerosity preferences and tuning profiles. In contrast, nearby putative inhibitory interneurons and projection neurons tended to show inverse tuning relative to one another.

The commonalities between PFC and NCL neurons also extended to functionally connected neuron pairs (Ditz et al. 2022). NCL neuron of

temporally coupled pairs consisting of nearby putative inhibitory interneurons and projection neurons tended to inhibit each other and showed inverse numerosity tuning profiles (Fig. 3C). This is the circuit operation required if interneurons sharpen tuning curves of projection neurons. In contrast, adjoining and functionally connected putative projection neurons showed similar numerosity tuning and usually became excited in synchrony (Fig. 3D). The combination of spike timing and category tuning properties in functionally connected putative inhibitory interneurons and projection neurons implies that these cell classes assume distinct roles in microcircuits of the crow NCL. Remarkably, the circuit operations witnessed in the crow NCL showed surprising correspondence with those observed in the primate PFC, despite their independent evolution.

CONCLUDING REMARKS

When evaluating the findings described in this article, two evolutionary scenarios may explain the apparent commonalities in circuit operations between corvids and primates. One scenario posits that the respective pallial microcircuits have been conserved over 640 million years of parallel evolution in birds and mammals (320 Mio years of evolution for each taxon since the last common ancestor) to maintain their functionalities in the avian nidopallium and the mammalian neocortex. Alternatively, the deciphered microcircuit mechanisms together with their building blocks, the excitatory projection neurons and the inhibitory interneurons, have been re-invented independently in the avian and mammalian lineages to serve similar computational functions in shaping and sharpening quantity tuning.

The latter hypothesis is supported by recent single-cell and spatial transcriptomics used in all tetrapod classes (amphibians, reptiles, birds, and mammals) to investigate cell-type evolution at the brain scale, and even prior to the phylogenetic reptile/avian–mammal separation (Tosches et al. 2018; Colquitt et al. 2021; Hain et al. 2022; Lust et al. 2022; Woych et al. 2022). The evidence from these combined studies pictures a complex scenario and suggests that the telencephalon is not composed of phylogenetically old and new regions but rather consists of a mosaic of conserved and new cell types (Faltine-Gonzalez and Kebschull 2022). A consistent finding is that the classes of inhibitory interneurons are largely conserved in the telencephalon of different species of tetrapods. In contrast, excitatory neurons in the telencephalon are much less conserved, arguing for the evolution of new excitatory cell types (Tosches et al. 2018; Hain et al. 2022; Lust et al. 2022; Woych et al. 2022). In a species of salamander (Amphibia), molecular and structural commonalities suggest that amphibian ventral pallium neurons are homologous to parts of the reptile DVR (a ventral pallium derivative) that is complemented by reptile-specific novelties. However, the amphibian dorsal pallium lacks molecular and cellular characteristics of excitatory cell types in the mammalian neocortex, a dorsal pallium derivative (Woych et al. 2022). This suggests that excitatory pyramidal neuron types in the mammalian six-layered neocortex are evolutionary novelties in mammals. Even though glutamatergic neurons in the avian DVR show greatest transcriptional similarities to neocortical projection neurons, these similarities are not restricted to specific layers but are found across neocortical layers (Colquitt et al. 2021). This finding is difficult to reconcile with the prediction of the cell-type homology hypothesis (nucleus-to-layer model) that glutamatergic neurons defined by processing level (i.e., thalamo-recipient, intra-pallially projecting, and extra-telencephalically projecting neurons) in specific nuclei of the bird pallium should be localized in specific neocortical layers that operate at the equivalent processing level in mammals. Rather, these insights suggest that the transcriptional similarities are at the level of function (i.e., projections and connections) within three major circuit components of the ventral pallium/neocortex (Fig. 1B). These cell-type differences across the vertebrate lineage together with the different regional origins of the reptilian/avian DVR and the mammalian neocortex corroborate the hypothesis that the functional similarities of the reptilian/avian DVR and neocortex are the result of convergence instead of homology. Notably, however, evolution seems to have re-

invented the major circuit components based on partial diversified and specialized neuron types in either or both lineages.

How exactly the emergence of old and new pallial territories and the intermingling of old (inhibitory interneurons) and new (primarily excitatory) neuron types can be explained is an open question. One scenario posits that new and old cell types may segregate into evolutionary newer and older pallial subregions that evolved potentially by duplication and divergence of sets of cell types (Kebschull et al. 2020). Alternatively, well-conserved telencephalic interneurons intermingle by (ontogenetic and phylogenetic) cell migration with newly arising excitatory cells in divergent regions of the pallium (Tosches et al. 2018; Colquitt et al. 2021). Whatever the precise mechanisms, based upon general circuitries inherited from common ancestry, the microscale networks in associative pallial areas reveal that both birds and mammals evolved similar neuronal and computational principles in parallel and partly independently based on convergent evolutionary forces (Nieder 2021c). It stands to reason that the microcircuit operations enabled by excitatory projection neurons and inhibitory interneurons constitute a superior solution to a common computation problem when representing abstract categories.

ACKNOWLEDGMENTS

This work was supported by DFG grants NI 618/10-1, NI 618/11-1 (SPP 2205), and NI 618/13-1 (FOR 5159) to A.N.

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Cold Spring Harb Perspect Biol 2023; doi: 10.1101/cshperspect.a041526