



HAL
open science

Cell-Specific Neuropharmacology

Sarah Mondoloni, Romain Durand-de Cuttoli, Alexandre Mourot

► **To cite this version:**

Sarah Mondoloni, Romain Durand-de Cuttoli, Alexandre Mourot. Cell-Specific Neuropharmacology. Trends in Pharmacological Sciences, 2019, 40 (9), pp.696-710. 10.1016/j.tips.2019.07.007. hal-02344518

HAL Id: hal-02344518

<https://hal.sorbonne-universite.fr/hal-02344518v1>

Submitted on 4 Nov 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Cell-specific neuropharmacology

2

3 Sarah Mondoloni^{1*}, Romain Durand-de Cuttoli^{1,2*} and Alexandre Mourot^{1*}

4

5

6 ¹ Neuroscience Paris Seine - Institut de Biologie Paris Seine (NPS – IBPS), CNRS, INSERM,

7 Sorbonne Université, Paris, France

8

9 ² Nash Family Department of Neuroscience, Center for Affective Neuroscience, and Friedman

10 Brain Institute, Icahn School of Medicine at Mount Sinai, New York, NY, USA

11

12 * All the authors contributed equally to the work

13

14

15 Correspondence : alexandre.mourot@upmc.fr (A. Mourot)

16

17

18

19

20

21 Key words: optogenetics, chemogenetics, tethered ligand, bump-hole, receptor-ligand pair,

22 photopharmacology

23

24 **Abstract**

25

26 Neuronal communication involves a multitude of neurotransmitters and an outstanding
27 diversity of receptors and ion channels. Linking the activity of cell surface receptors and ion
28 channels in defined neural circuits to brain states and behaviors has been a key challenge in
29 neuroscience, since cell-targeting is not possible with traditional neuropharmacology. We
30 review here recent technologies that enable the effect of drugs to be restricted to specific cell
31 types, thereby allowing acute manipulation of the brain's own proteins with circuit specificity.
32 We highlight the importance of developing cell-specific neuropharmacology strategies for
33 decoding the nervous system with molecular- and circuit-precision, and for developing future
34 therapeutics with reduced side effects.

35

36

37

38 **Probing the nervous system with cell-targeted drugs**

39

40 Investigating the function of neurotransmitter receptors and ion channels has greatly
41 benefited from both pharmacological and genetic techniques. Conditional mutagenesis and
42 virally-delivered **shRNAs** enable the manipulation of proteins with molecular specificity and in
43 targeted brain circuits, notably through the use of **cre/lox recombination**. Yet, these
44 techniques do not have sufficient temporal resolution to establish a direct link between the
45 activation of receptors and the modulation of circuits and behavior. In addition, they can lead
46 to developmental alterations that compensate for those induced by the deletion/mutation of
47 the receptor. In contrast, conventional pharmacology offers acute and often reversible control
48 of endogenous proteins, enables graded alterations by varying drug concentration, and can
49 be applied at any time in development. Nevertheless, pharmacology suffers from lack of
50 functional selectivity, since small chemicals affect all types of neurons cannot be cell-targeted.
51 This is especially an issue considering the wide distribution of ion channels and receptors in
52 the brain, and the various functions they have in different cells or networks. Local distribution
53 of drugs to precise brain regions may afford anatomical specificity, but has major drawbacks,
54 such as the difficulty to control dosage and diffusion, and the inability to target specific
55 neuronal types. Making small chemicals photocontrollable using caged compounds or
56 photoswitches permits cellular or even subcellular optical targeting at the single cell level, and
57 improves spatio-temporal control *in vivo* [1,2]. Yet, even with the most sophisticated light
58 source, controlling receptors located on different cell types within the same circuit in an intact
59 brain is elusive with optical techniques alone. The ability to acutely control signaling proteins
60 in a complex environment such as the nervous system in a cellular- and circuit-specific manner
61 and in the behaving animal should accelerate progress in our molecular understanding of
62 brain function (Figure 1A).

63

64 The idea behind cell-specific pharmacology is to combine the acute onset of pharmacology
65 with the cellular and molecular precision of genetics, to achieve acute control of signaling
66 proteins in a cell-specific fashion. To this aim, several chemogenetic strategies have recently
67 been developed, which we classify here in three categories (Figure 1, key figure, Table 1). The
68 receptor-ligand pair approach (Figure 1B) consists in re-engineering proteins to make them
69 sensitive to synthetic ligands. The key outcome is an increase in potency of the synthetic ligand

70 compared to the natural one (Figure 1C). The **tethered**-ligand approach (Figure 1D) relies on
71 the anchoring of a ligand to the cell surface and results in an increased local concentration of
72 the ligand. Anchoring can be performed either to a membrane-embedded element
73 (membrane-tethered) or to a genetically-modified receptor (receptor-tethered). Finally, the
74 last approach is to selectively deliver drugs to the cytoplasm of targeted cells, either using
75 enzyme-prodrug pairs or facilitated diffusion through large ion channels (Figure 1E). Cell-
76 specific neuropharmacology approaches provide the ability to test the function of receptors
77 on specific types of neurons with unprecedented cellular precision (e.g. pre- vs. post-synaptic
78 cells, or two different cell types within the same circuit) [3,4]. They also offer a unique
79 opportunity to test the benefits of cell-targeted drugs for neurological and neuropsychiatric
80 disorders. We review here these techniques, with a special focus on surface receptors and ion
81 channels, highlighting their potentials and pitfalls, and the challenges they meet for *in vivo*
82 use in rodents and for clinical applications.

83

84 **The receptor-ligand pair approach**

85

86 One central problem of traditional pharmacology is to identify small molecules that interact
87 with a desired protein target with high specificity. This is especially challenging for proteins
88 that belong to large protein families and therefore share a high degree of homology with other
89 proteins in the cell. To address this shortcoming, a chemo-genetic strategy named **bump-hole**
90 was developed, allowing inhibition of specific alleles of protein kinases [5]. The idea is to
91 genetically create a hole on the catalytic active site of the protein, and to chemically modify
92 the inhibitor, with a corresponding bump (Figure 1B). The synthetic ligand is **orthogonal**: it
93 confers high specificity to the engineered enzyme, without affecting wild-type (WT) kinases.
94 Importantly, the engineered kinase is a non-orthogonal mutant protein, i.e. it can still
95 phosphorylate endogenous substrates. A wide range of kinase-inhibitor pairs were generated,
96 displaying incomparable potency and specificity compared to known inhibitors [5].

97

98 Inspired by this approach, neuroscientists developed orthogonal receptor-ligand pairs, the
99 most widely used being the Designer Receptors Exclusively Activated by Designer Drugs
100 (**DREADDs**) [6,7]. DREADDs are modified G-protein coupled receptors (GPCRs) engineered
101 through directed molecular evolution, that are insensitive to their natural ligands but sensitive

102 to synthetic agonists (Figure 2A). The original DREADDs (hM3Dq and hM4Di) are based on
103 human M3 and M4 muscarinic receptors, which couple to Gq and Gi, respectively [6]. hM3Dq
104 and hM4Di are made insensitive to acetylcholine (ACh), sensitive to the synthetic ligand
105 clozapine-N-oxide (CNO), and importantly show minimal basal activity in the absence of
106 chemical activation (but see [8]). hM3Dq is classically used for enhancing neuronal activity,
107 while hM4Di is used for neuronal inhibition. Newer DREADDs include GsD that couples to Gs,
108 hM4D^{nrxn} that is axonally targeted and affords pre-synaptic inhibition, and a κ -opioid-derived
109 DREADD (KORD) that operates with salvinorin B [9], a compound distinct from CNO, thus
110 allowing multiplexed and bidirectional modulation of neuronal activity and behavior.

111

112 Receptor-ligand pairs have also been developed for ligand gated ion channels (LGICs, Figure
113 2B). The ligand binding domain (LBD) of the α 7 nicotinic acetylcholine receptor (nAChR),
114 referred to as pharmacologically selective actuator module (**PSAM**), was engineered to
115 respond solely to synthetic molecules called pharmacological selective effector molecules
116 (**PSEM**) [10,11]. Activation of PSAM by PSEMs induces either cation, calcium or chloride influx,
117 depending on the ion pore domain (IPD) spliced onto the LBD (serotonin 5HT3, α 7-nAChR or
118 glycine receptor IPD, respectively). Hence PSAMs can be used to either drive or suppress
119 neuronal activity, or to increase intracellular calcium, in genetically-targeted neurons.
120 DREADDs, and to a lesser extent PSAMs, have proven extremely valuable tools for the
121 manipulation of circuits with cellular specificity, providing crucial information as to how
122 circuits shape behavior [7,12]. However, because they are no longer sensitive to their cognate
123 ligands, DREADDs and PSAMs are constraint to decode the nervous system at the circuit level,
124 and cannot be used for the molecular dissection of the role of endogenous GPCR or LGIC
125 signaling in the modulation of circuits and behaviors.

126

127 With the advent of optogenetics [13], light-based strategies for controlling brain proteins have
128 emerged, affording improved spatio-temporal resolution over chemical approaches [1].
129 Notably, light-controllable adrenergic, opioid, serotonergic and glutamatergic GPCRs (**Opto-**
130 **XR**s) have been engineered [14,15]. Opto-XRs are chimeric proteins, usually engineered with
131 a mammalian opsin (e.g. rhodopsin or melanopsin) and the intracellular loops and C-terminal
132 tail of endogenous GPCRs (Figure 2C). In addition to trafficking and signaling like their native
133 counterparts, OptoXRs are photo-activatable, offering the possibility to mimic the spatio-

134 temporal dynamics of neuromodulator signaling *in vivo*. Nevertheless, Opto-XRs bind retinal
135 and therefore lack responsiveness to endogenous ligands, restricting their use, as with
136 DREADDS, to a circuit-level understanding of brain function.

137

138 Dissecting the role of endogenous receptors and channels in behaviors requires maintaining
139 their natural pharmacology and signaling properties. To this aim, two receptor-ligand pair-like
140 approaches have been developed for GABA_A receptors (GABA_ARs) and nAChRs. GABA_AR
141 signaling is potentiated by the allosteric modulator zolpidem, yet only when the $\gamma 2$ subunit is
142 present in the receptor. A single mutation (phenylalanine to isoleucine) at position 77 on the
143 $\gamma 2$ subunit is sufficient to convert a zolpidem-sensitive into a zolpidem-insensitive receptor
144 (Figure 2D) [16]. In transgenic mice expressing $\gamma 2(\text{Ile77})$, sensitivity to zolpidem can be
145 restored in a tissue-specific fashion using Cre-recombinases that switch $\gamma 2(\text{Ile77})$ to $\gamma 2(\text{Phe77})$.
146 Zolpidem-sensitivity was notably restricted to cerebellar Purkinje neurons, to show that
147 potentiation of GABAergic inhibition in these cells induces motor deficits [17]. Even though
148 motor deficits had been observed after zolpidem administration in WT mice, interpretation
149 was ambiguous considering the profound sedative effects of this compound. Furthermore,
150 mice with a deletion of $\gamma 2$ in Purkinje cells show no motor deficit, emphasizing the importance
151 of developing cell-specific pharmacology approaches for acute interventions. Nevertheless, it
152 should be noted that this strategy requires triple crosses of mouse lines, making it
153 technologically demanding.

154

155 In nAChRs, the strategy was referred to as gain-of-function mutations [18]. The idea is to
156 increase agonist sensitivity in a subtype-specific fashion using site-directed mutagenesis, and
157 to use sub-threshold doses of nicotine for isoform-selective activation (Figure 2E). The leucine
158 residue in position 9' on the transmembrane (TM) segment M2 is a conserved residue that,
159 when mutated to alanine, serine or threonine in the α subunit, considerably reduces the
160 energy required to open the channel, resulting in a "hypersensitive" mutant with increased
161 agonist sensitivity [18]. Using the Cre-lox technology, expression of such hypersensitive
162 mutants could be restricted to specific neurons such as GABAergic cells of the ventral
163 tegmental area or cholinergic neurons of the medial habenula, unveiling new roles for $\alpha 4$
164 nAChRs in reward and anxiety, respectively [19,20]. However, it should be noted that these

165 mutant receptors are also more sensitive to endogenous acetylcholine (ACh), which may
166 result in unintended neuronal adaptations.

167

168 **The tethered-ligand approach**

169

170 The overall strategy is to increase local concentration of the drug at the cell surface through
171 covalent attachment [21]. One major advantage of this approach is that once bio-conjugation
172 is achieved, there is no need for reapplication of the drug.

173

174 ***Membrane-tethered ligands***

175

176 A first example is based on genetically-encoded ligands that are self-embedded in cell
177 membranes. The fusion construct is composed of a peptide linked by a flexible linker to the
178 extracellular side of the membrane, either through a TM segment or a glycosyl-phosphatidyl-
179 inositol (**GPI**) anchor (Figure 3A) [22-27]. The peptide ligand can either be an agonist (t-
180 peptide) or an antagonist (t-toxin). This versatile approach has been successfully applied to
181 activate class B GPCRs [22] and to inhibit specific voltage-gated sodium (Na_v) and calcium (Ca_v)
182 channels as well as nAChRs [24-27]. Toxins can be extremely specific for a particular type of
183 ion channel, enabling blockade of $\text{Na}_v1.7$ without affecting $\text{Na}_v1.8$ for instance [28]. However,
184 since the ligand is permanently expressed at the membrane, the action of t-peptides and t-
185 toxins is irreversible. T-toxin expression can be placed under the control of a **Tet-on/Tet-off**
186 **system**, allowing antagonism to be triggered on and off, yet still with very slow kinetics (days)
187 [24]. Consequently, these tools have been used for chronic inhibition of neuronal activity and
188 genetic dissection of neurophysiological circuits rather than for acute, cell-specific
189 pharmacology. T-toxins were notably used in freely-moving mice, where chronic inhibition of
190 $\text{Ca}_v2.1$ and $\text{Ca}_v2.2$ allowed probing the role of thalamo-striatal excitatory synaptic
191 transmission in the susceptibility to social stress [27].

192

193 An extension of this approach is to include in the construct a photosensitive group to afford
194 reversibility. Notably, the **light-oxygen voltage** (LOV) protein domain from plants was used to
195 produce Lumitoxins, light-controllable membrane-tethered toxins (Figure 2B) [29]. LOV
196 domains incorporate a flavin chromophore, ubiquitously present in mammalian cells, and

197 changes conformation upon illumination with blue light. In darkness, Lumitoxins produce
198 sustained block of voltage-gated potassium (Kv) channels, while illumination results in rapid
199 (seconds) channel unblock. The LOV domain returns to its resting state slowly in darkness,
200 restoring blockade within minutes. Specific Kv homologues such as Kv1.1, Kv1.2 or Shaker can
201 be photosensitized using appropriate membrane-tethered toxins. However, this technique
202 has not yet been extended to other protein families and has not been deployed *in vivo*.

203

204 Another strategy, called Drug Acutely Restricted by Tethering (**DART**), relies on a bacterial
205 enzyme called **HaloTag** for capturing drugs at the cell surface [3]. HaloTag is a self-labeling
206 enzyme that catalyzes the covalent attachment of synthetic molecules containing a HaloTag
207 Ligand (HTL) with very high efficiency and specificity (Box 1). In DART, the HaloTag is expressed
208 at the cell surface through a TM domain. The synthetic ligand is composed of an active drug
209 linked to the HTL through a Poly-Ethylene Glycol (**PEG**) flexible linker. Once infused, it attaches
210 to the HaloTag, resulting in a hundred-fold elevation of drug concentration at the cell surface.
211 This strategy is unique in that it offers acute pharmacological manipulation (seconds to
212 minutes) of native receptors with cellular specificity. However, the effect is only very slowly
213 reversible (days). DART has been applied to AMPA receptors (AMPA receptors) and metabotropic
214 muscarinic receptors (mAChRs), showing that the method can be applied to different receptor
215 types . Specific inhibition of AMPARs in distinct neuronal populations of the dorsal striatum
216 (D1 versus D2 neurons) revealed that activity of these receptors is causally linked with the
217 akinesia observed in a mouse model of Parkinson's disease. Moreover, antagonism of AMPARs
218 expressed on D2-, but not D1-, neurons had therapeutic effects on motor dysfunction,
219 illustrating the power of targeting drugs to specific cell types.

220

221 ***Receptor-tethered ligands***

222

223 Various strategies have been developed to tether ligands directly to their receptors. In the
224 RECON (REductively Cleavable agONist) approach, a GPCR is N-terminally fused to a **SNAP-**
225 **tag** [30], another type of self-labeling tag. The tethered ligand combines a peptide agonist for
226 either class A or B GPCR, a central PEG linker bearing a disulfide bridge, and a SNAP-tag
227 substrate. This synthetic ligand covalently and specifically attaches to the SNAP-tag, resulting
228 in permanent receptor activation. The disulfide bridge can be cleaved with redox agents,

229 resulting in slow agonist dissociation. This method should be especially useful for studying
230 GPCR activation and internalization *in vitro*; however, its use for neuropharmacology is
231 elusive.

232

233 Increasing local agonist concentration at the receptor surface does not necessarily require
234 covalent attachment. Another design is to install a **His-tag** on a GPCR, and to use a Metal-
235 complex Agonist Conjugate (**MAC**) that binds with high affinity to the His-tag through
236 coordination tethering (Figure 3D) [31]. Affinity of the synthetic ligand is 10-100 higher for the
237 engineered than for the WT receptor. Interaction between MAC and the His-tag is not
238 covalent, hence activation is reversible. The MAC strategy was used for cell-specific control of
239 class A GPCRs (β 2 adrenoreceptors and mAChRs), but its efficacy *in vivo* has not been reported
240 yet.

241

242 One major drawback of tethered ligands is irreversibility of action. One solution to this issue
243 is to incorporate a chemical photoswitch in the ligand, and use light to trigger
244 binding/unbinding. This can be achieved by anchoring a photoswitchable tethered ligand (**PTL**)
245 onto a cysteine-substituted receptor (Figure 3E). The cysteine mutation is incorporated in
246 proximity to a ligand-binding site. The PTL is made of three elements: a **maleimide** moiety,
247 which is a **thiol**-reactive group for attachment to cysteines; a central **azobenzene**
248 photoswitch; and a bioactive ligand (agonist, antagonist or pore-blocker). Light is used to
249 reversibly change the geometry of the photoswitch from elongated to twisted, which triggers
250 binding/unbinding. This opto-chemogenetic strategy allows reversible control of receptors
251 with very high spatial and temporal precision. The PTL approach has proven to be highly
252 versatile. It has been applied to potassium channels [32-34], ionotropic [35-37] and
253 metabotropic [38] glutamate receptors, nAChRs [4,39], GABA_ARs [40,41], dopamine receptors
254 [42] as well as P2X receptors [43]. It was used to probe neurotransmission in various neuronal
255 settings, both *ex* and *in vivo* in zebrafish and mice [1]. In zebrafish, the photoswitch can simply
256 be added to the swimming water, but in mice it has to be locally delivered. Despite this
257 drawback, the PTL approach has been applied in the living mouse, notably for restoring vision
258 to blind mice [44], for manipulating action potential firing [45] and GABAergic inhibition [41]
259 in the visual cortex, or for controlling nicotinic transmission in the ventral tegmental area and
260 addiction-related behaviors [4]. One potential shortcoming of PTLs is their non-selective

261 attachment to endogenous cysteines, even though no adverse effect has been observed so
262 far [4,41].

263

264 More specific bioconjugation (Box 1) can be achieved with the Photoswitchable Orthogonal
265 Remotely Tethered Ligand (**PORTL**) approach, which uses self-labelling enzymes such as **SNAP-**
266 or **CLIP-tags** (Figure 3F) [46-48]. These self-labeling tags can be fused directly to receptors
267 [46,47] or alternatively to nanobodies [48], an interesting alternative for proteins for which
268 incorporation of the tag is prohibited. Light is used to change the geometry of the ligand, and
269 thereby its affinity for the protein. This technology has so far only been applied to
270 metabotropic glutamate receptors, and was used to restore patterned vision in a blind mouse
271 model [49].

272

273 Another alternative for site-specific bioconjugation is the Bio-Orthogonal Ligand Tethering
274 (**BOLT**) technique, which is based on the incorporation of unnatural amino acids (**UAA**) in
275 proteins [50]. The UAA is used as a biorthogonal handle for attachment of a synthetic ligand
276 through **click-chemistry**. BOLT demonstrated selective inhibition of kinases in mammalian
277 cells, and can be made photo-reversible by introducing a photoisomerizable group to the
278 ligand (photoBOLT). Expansion of the genetic code in the mouse is technically challenging[51],
279 but the recent generation of transgenic animals carrying a tRNA synthetase / tRNA pair into
280 their genome should facilitate future use [52].

281

282 **Intracellular delivery approaches**

283

284 Intracellular, cell-specific delivery can also be achieved, allowing targeting not only cell-
285 surface receptors but also enzymes and signaling pathways (Figure 1E). Two different
286 approaches have been described.

287

288 ***The enzyme-prodrug pair approach***

289

290 This approach relies on selective enzyme-substrate pairs to convert an inert prodrug into an
291 active molecule (Figure 1E) [53]. The drug is masked by a disposable blocking group that is
292 hydrolyzed specifically by an exogenous enzyme, but not by native ones. Expression of the

293 specific enzyme in genetically-targeted cells allows unmasking the drug in a cell-specific
294 fashion. The challenges were to develop an ester masking group with high stability towards
295 hydrolysis by endogenous esterases, and to find an esterase that would hydrolyze this ester
296 bond with high efficiency. Screening resulted in the discovery of porcine liver esterase (**PLE**),
297 an enzyme that efficiently hydrolyzes the cyclopropylmethyl carboxyl (**CM**) ester masking
298 group [53]. More recently, another selective enzyme-substrate pair was developed, based on
299 engineered variants of E. coli nitroreductase (**NTR**) and a nitroimidazol (**NM**) masking group
300 [54]. This strategy has proven highly generalizable to various masked small molecules such as
301 fluorophores, calcium indicators, enzyme inhibitors, cAMP analogs or ion channel blockers
302 [53-55]. Notably, the masked compound CM-MK801 was used to confirm, in brain slices, the
303 role of dopamine neuron-expressed NMDA receptors in cocaine-induced plasticity [55]. Both
304 the CM and NM groups were shown to be highly stable in neurons, an important requirement
305 for cell-specificity. That said, care must be taken because drugs that are too membrane
306 permeable may diffuse out of the target neuron and affect nearby cells non-selectively. This
307 limitation can be circumvented, for instance by increasing polarity of the compound [54]. The
308 biggest challenge for future applications remains to use this technology *in vivo*. So far, the
309 limited aqueous solubility of the masked compounds precludes direct brain delivery. In
310 addition, systemic application of CM-masked drugs is prohibited as well because CM is not
311 resistant to esterases expressed in the periphery.

312

313 ***Facilitated diffusion through large ion-channel pores***

314

315 Another approach is based on the selective intracellular diffusion of membrane-impermeant
316 drugs through large ion channels (Figure 1E). The capsaicin TRPV1 and some P2X receptors
317 open a very large pore when activated, allowing permeation of large organic cations [56,57].
318 This biophysical property was ingeniously exploited to facilitate the entry of QX-314, a
319 membrane-impermeant lidocaine derivative, into pain-sensing neurons [58]. QX-314 is
320 normally inert on neurons because it has an intracellular site of action in Na_vs. However, it can
321 selectively enter nociceptors by diffusing through open TRPV1 channels, which are abundant
322 in these cells but virtually absent in other neurons. QX-314 remains trapped inside pain
323 neurons for hours, resulting in long-lasting local analgesia [58-60]. To gain rapidly reversible
324 control over nociception, we designed a photoswitchable version of QX-314, named **QAQ** [61-

325 63]. QAQ can rapidly and reversibly block blocks Na_v s in nociceptors, switching pain signaling
326 on and off upon illumination with the appropriate wavelength of light.

327

328 Unlike all the methods presented in this review, this strategy does not necessarily require
329 genetic manipulation. Rather, it exploits the sparse distribution of TRPV1 channels or P2X
330 receptors to achieve targeted cell loading, and thus bears potential therapeutic interest. So
331 far, QX-314 and QAQ were co-administered with capsaicin to enable selective cell entry. Yet,
332 recent studies suggest that capsaicin may not always be needed, since TRPV1 channels in
333 central terminals are extensively hyperactive in neuropathic pain models [64]. Similarly, the
334 retina was shown to be highly remodeled in animal models of retinal degeneration [65], with
335 P2X receptors functionally upregulated in retinal ganglion cells [66]. This feature was exploited
336 to deliver photoswitchable blockers of potassium channels [61,67] specifically to OFF-ganglion
337 cells, thereby restoring visual responses to blind retinas [65,66].

338

339 **Concluding remarks**

340

341 Investigating the role of individual receptors and ion channels in particular brain regions
342 requires methods for perturbing protein activity selectively, acutely, reversibly and in a cell-
343 specific fashion, ideally in the behaving animal. Diverse methods are being developed toward
344 this goal. Yet no method is universal, and virtually all have shortcomings, especially when
345 considering their use *in vivo*. One important limitation lies in the limited therapeutic window
346 for selective agonism / antagonism, which is classically in the range 10-100 fold (Table 1).
347 Recent studies demonstrate that with some optimization, very potent agonists with
348 exceptional selectivity (>10 000 fold) can be generated for PSAMs [11] and DREADDs [68],
349 suggesting that such selectivity should be in principle attainable for other designer receptors.
350 Full orthogonality can even be achieved, for instance using light-based methods (after ligand
351 bioconjugation for PTLs and PORTLs). Yet, there is still a need for orthogonal labeling motifs
352 that are efficient at lower doses (Box 1).

353

354 There is also a need for caution and appropriate controls when using chemogenetic
355 approaches, even when reported to be fairly orthogonal. For instance, CNO was originally
356 selected because of its excellent drug-like properties, but recent reports show that *in vivo* it is

357 metabolically back-converted to clozapine, a molecule that not only activates DREADDs but
358 also many other endogenous GPCRs [69]. Importantly, non-CNO analogues with improved
359 selectivity have been developed, notably compound 21 [70] and perlapine [68], circumventing
360 this potential issue.

361

362 Another important limitation to consider is invasiveness. DREADD activators, PSEMs, nicotine
363 and zolpidem have rapid central nervous system (CNS) penetration and distribution in mice
364 and can therefore be applied systemically [7,17,18,71]. But other approaches require local
365 drug delivery in brain tissue through a cannula guide, either because of the instability of the
366 compound in aqueous medium (e.g. maleimide-based PTLs) or because of poor blood brain
367 penetration (e.g. DART), or both. Methods for improved systemic delivery are awaited.
368 Similarly, the optical tools described in this review classically work with visible light (Table 1)
369 and therefore require local light delivery with a chronically implanted optic fiber. Red-shifted
370 chromophores that operate at more deeply-penetrating wavelengths such as near-infra-red
371 light are currently under development [72] and should facilitate remote, transcranial control
372 in the future.

373

374 Another important aspect to consider is receptor-type specificity. Techniques like DART or
375 intracellular delivery methods target native receptors and therefore cannot differentiate
376 between different receptor isoforms expressed on the same cell. Toxin-based methods
377 provide increased selectivity but whether they can be used for acute and reversible control of
378 receptors and ion channels in vivo is unclear. On the other hand, methods that require genetic
379 engineering of receptors, like PTL or PORTL, provide absolute receptor-type specificity and can
380 help dissect the role of individual receptor subtypes in a circuit. However, molecular specificity
381 comes at a cost: the requirement for ectopic expression of the target protein, which may
382 affect expression level and/or patterns. Methods for overcoming this issue include the
383 generation of transgenic knock-in animals [41]- ideally in a tissue-specific fashion- or the use
384 of a subunit replacement strategy [34].

385

386 Finally, these tools bear strong potential not only for research purposes in animal models, but
387 also for therapeutic applications in humans. Indeed, targeting drugs to particular neuronal
388 populations may improve therapeutic efficacy, while decreasing the side effects associated

389 with insufficient selectivity of conventional approaches. For instance, QX-314 or QAQ can
390 selectively block the function of pain-sensing neurons in rodents, while leaving other sensory
391 modalities unaffected [58,59,62], and do not require genetic modification, making them
392 potential drug-like candidates for pain-selective local anesthesia in humans. Approaches
393 requiring genetic manipulation are also being explored to treat CNS diseases in a titrated and
394 cell-specific manner. This includes strategies for restoring the balance of excitation/inhibition
395 selectively in epileptogenic zones, or for treating movement disorder in Parkinson's disease.
396 The DART technology for instance revealed that antagonizing AMPARs expressed on D2
397 neurons of the basal ganglia was much more efficient at improving motor dysfunction than
398 global antagonism through D1 and D2 neurons. Yet it is not clear how this finding can be
399 translated into human therapy. DREADDs and PSAMs are currently progressing into non-
400 human primates [73,74], an important step towards being used as treatment to people. In
401 addition, hM4Di, KORD and new-generation PSAMs can be potently activated by low doses of
402 olanzapine [75], salvinorin B [9] and varenecline [71], respectively, three drugs that are
403 already clinically approved, thus facilitating translation to humans. Despite these important
404 advances, considerable obstacles for implementing such approaches to the clinic remain,
405 notably those associated with gene therapy and, to a lesser extent, drug delivery and
406 selectivity.

407

408 **Table 1: Cell-specific neuropharmacology approaches.**

409 N.R.: not reported; N.A.: not applicable

Tool Name	Receptor	Ligand	On timescale	Off timescale	Therapeutic window (fold)	Application	In vivo application	Refs
Receptor-ligand pairs								
DREADDS	Synthetic GPCR	Synthetic (CNO, perlapine...)	s-min	min-hour	100-10000	On/off control of neuronal activity	Drosophila, mice, rats, monkeys	[6,7]
PSAM/PSEM	Synthetic LGIC	Synthetic (22S, 89S...)	s-min	min-hour	30->10000	On/off control of neuronal activity	Mice	[10,11]
Opto-XR	Opsin-GPCR chimera	Retinal + Blue light	ms-s	ms-s	Fully orthogonal (light)	Activation of G protein signaling	Mice	[14,15]
Zolpidem-insensitive GABA _A R	Mutant GABA _A R	Synthetic (Zolpidem)	s-min	min-hour	>600	Modulation of GABA _A Rs	Mice	[17]
Gain of function nAChRs	Mutant nAChR	Exogenous (Nicotine) and endogenous (ACh)	s-min	min-hour	10-100	Activation of nAChR subtypes	Mice	[19,20]
Membrane-tethered ligands								
t-toxins and t-peptides	Native receptors and ion channels	Genetically-encoded toxins or peptides	Always on (days with Tet-on system)	Irreversible (days with Tet-off system)	N.A. (constitutive)	Genetic dissection of circuits	Drosophila, zebrafish, mice	[22-27]
Lumitoxin	Native receptors and ion channels	Genetically-encoded toxins + blue light	min	s	Fully orthogonal (light)	Block of ion channel subtypes	N.R.	[29]
DART	Native AMPA receptors	HaloTag-reactive ligand	s-min	days	30-300	Antagonism of AMPARs and mAChRs	Mice	[3]
Receptor-tethered ligands								
RECON	SNAP-tagged GPCR	SNAP-reactive ligand	s-min	Irreversible (min with redox agent)	N.A.	Activation and internalization of GPCRs	N.R.	[30]
MAC	His-tagged GPCR	Metal complex-agonist conjugate	s-min	min	10-100	Activation of GPCRs	N.R.	[31]
PTL	Cysteine-substituted receptor	Thiol-reactive ligand + UV-visible light	ms-s	ms-s	N.A. (orthogonal after attachment)	On/off control of receptors and ion channels	Zebrafish, mice	[4,32-43]
PORTL	SNAP- or CLIP-tagged GPCR or nanobody	SNAP- or CLIP-reactive ligand + UV-visible light	ms-s	ms-s	N.A. (orthogonal after attachment)	On/off control of receptors	Mice	[46-48]
iBOLT (and photoBOLT)	Receptor mutated with unnatural aminoacid	Click chemistry-reactive ligand (+ UV light)	min-h	Irreversible (min with light)	N.A.	Inhibition of protein activity (reversible with light)	N.R.	[50]
Intracellular delivery								

Enzyme-pro drug pair	Native proteins	Masked drug	min	Irreversible	N.A.	Control of protein activity	N.R.	[53-55]
Facilitated diffusion through large ion channels	Native proteins	Membrane-impermeant and cationic (+UV-visible light)	Min (ms-s with light)	Days (ms-s with light)	N.A.	Block of ion channels (on/off with light)	Mice, rats	[58-60,62, 63,65, 66]

410

411 **Acknowledgement:** We wish to thank Fabio Marti and Philippe Faure (Sorbonne Université)
412 for their comments on the manuscript. This work was supported by grants from the Fondation
413 pour la Recherche Médicale FRM (Equipe FRM DEQ2013326488), the Brain and Behavior
414 Research Foundation (NARSAD Young Investigator Grant), the Agence Nationale de la
415 Recherche (ANR-JCJC), the Institut National Du Cancer (TABAC-16-022) and the Fondation de
416 France (Fondation Médisite). SM and RDC were recipient of a 4th year PhD fellowship from
417 FRM (FDT201904008060 and FDT20170437427, respectively).

418 **References**

419

420 1 Paoletti, P. *et al.* (2019) Optical control of neuronal ion channels and receptors.
421 *Nat Rev Neurosci* under review,

422 2 Hüll, K. *et al.* (2018) In Vivo Photopharmacology. *Chem. Rev.* DOI:
423 10.1021/acs.chemrev.8b00037

424 3 Shields, B.C. *et al.* (2017) Deconstructing behavioral neuropharmacology with
425 cellular specificity. *Science* 356,

426 4 Durand-de Cuttoli, R. *et al.* (2018) Manipulating midbrain dopamine neurons and
427 reward-related behaviors with light-controllable nicotinic acetylcholine
428 receptors. *eLife* 7, 15991

429 5 Bishop, A.C. *et al.* (2000) A chemical switch for inhibitor-sensitive alleles of any
430 protein kinase. *Nature* 407, 395–401

431 6 Armbruster, B.N. *et al.* (2007) Evolving the lock to fit the key to create a family of
432 G protein-coupled receptors potently activated by an inert ligand. *Proceedings of*
433 *the National Academy of Sciences* 104, 5163–5168

434 7 Roth, B.L. (2016) DREADDs for Neuroscientists. *Neuron* 89, 683–694

435 8 Saloman, J.L. *et al.* (2016) Gi-DREADD Expression in Peripheral Nerves Produces
436 Ligand-Dependent Analgesia, as well as Ligand-Independent Functional Changes
437 in Sensory Neurons. *J. Neurosci.* 36, 10769–10781

438 9 Vardy, E. *et al.* (2015) A New DREADD Facilitates the Multiplexed Chemogenetic
439 Interrogation of Behavior. *Neuron* 86, 936–946

440 10 Magnus, C.J. *et al.* (2011) Chemical and Genetic Engineering of Selective Ion
441 Channel-Ligand Interactions. *Science* 333, 1292–1296

442 11 Magnus, C.J. *et al.* (2019) Ultrapotent chemogenetics for research and potential
443 clinical applications. *Science* DOI: 10.1126/science.aav5282

444 12 Atasoy, D. and Sternson, S.M. (2018) Chemogenetic Tools for Causal Cellular and
445 Neuronal Biology. *Physiological Reviews* 98, 391–418

446 13 Kim, C.K. *et al.* (2017) Integration of optogenetics with complementary
447 methodologies in systems neuroscience. *Nat Rev Neurosci* 18, 222–235

448 14 Airan, R.D. *et al.* (2009) Temporally precise in vivo control of intracellular
449 signalling. *Nature* DOI: 10.1038/nature07926

- 450 15 Spangler, S.M. and Bruchas, M.R. (2017) Optogenetic approaches for dissecting
451 neuromodulation and GPCR signaling in neural circuits. *Current Opinion in*
452 *Pharmacology* 32, 56–70
- 453 16 Buhr, A. *et al.* (1997) Subtle changes in residue 77 of the gamma subunit of
454 alpha1beta2gamma2 GABAA receptors drastically alter the affinity for ligands of
455 the benzodiazepine binding site. *Journal of Biological Chemistry* 272, 11799–
456 11804
- 457 17 Wulff, P. *et al.* (2007) From synapse to behavior: rapid modulation of defined
458 neuronal types with engineered GABAA receptors. *Nature Neuroscience* 10, 923–
459 929
- 460 18 Drenan, R.M. and Lester, H.A. (2012) Insights into the Neurobiology of the
461 Nicotinic Cholinergic System and Nicotine Addiction from Mice Expressing
462 Nicotinic Receptors Harboring Gain-of-Function Mutations. *Pharmacological*
463 *Reviews* 64, 869–879
- 464 19 Ngolab, J. *et al.* (2015) Functional Upregulation of $\alpha 4^*$ Nicotinic Acetylcholine
465 Receptors in VTA GABAergic Neurons Increases Sensitivity to Nicotine Reward. *J.*
466 *Neurosci.* 35, 8570–8578
- 467 20 Pang, X. *et al.* (2016) Habenula cholinergic neurons regulate anxiety during
468 nicotine withdrawal via nicotinic acetylcholine receptors. *Neuropharmacology*
469 107, 294–304
- 470 21 Leippe, P. *et al.* (2017) Specificity and Speed: Tethered Photopharmacology.
471 *Biochemistry* 56, 5214–5220
- 472 22 Fortin, J.-P. *et al.* (2009) Membrane-tethered ligands are effective probes for
473 exploring class B1 G protein-coupled receptor function. *Proceedings of the*
474 *National Academy of Sciences* 106, 8049–8054
- 475 23 Choi, C. and Nitabach, M.N. (2013) Membrane-Tethered Ligands: Tools for Cell-
476 Autonomous Pharmacological Manipulation of Biological Circuits. *Physiology* 28,
477 164–171
- 478 24 Auer, S. *et al.* (2010) Silencing neurotransmission with membrane-tethered
479 toxins. *Nature Methods* DOI: 10.1038/nmeth.1425
- 480 25 Ibañez-Tallon, I. and Nitabach, M.N. (2011) Tethering toxins and peptide ligands
481 for modulation of neuronal function. *Current Opinion in Neurobiology* DOI:

482 10.1016/j.conb.2011.11.003

483 26 Ibañez-Tallon, I. *et al.* (2004) Tethering Naturally Occurring Peptide Toxins for
484 Cell-Autonomous Modulation of Ion Channels and Receptors In Vivo. *Neuron* 43,
485 7–7

486 27 Christoffel, D.J. *et al.* (2015) Excitatory transmission at thalamo-striatal synapses
487 mediates susceptibility to social stress. *Nature Neuroscience* 18, 962–964

488 28 Stürzebecher, A.S. *et al.* (2010) An in vivo tethered toxin approach for the cell-
489 autonomous inactivation of voltage-gated sodium channel currents in
490 nociceptors. *The Journal of Physiology* 588, 1695–1707

491 29 Schmidt, D. *et al.* (2014) A fully genetically encoded protein architecture for
492 optical control of peptide ligand concentration. *Nature Communications* 5, 1–8

493 30 Podewin, T. *et al.* (2018) Conditional and Reversible Activation of Class A and B G
494 Protein-Coupled Receptors Using Tethered Pharmacology. *ACS Cent. Sci.* 4, 166–
495 179

496 31 Kubota, R. *et al.* (2018) Chemogenetic Approach Using Ni(II) Complex-Agonist
497 Conjugates Allows Selective Activation of Class A G-Protein-Coupled Receptors.
498 *ACS Cent. Sci.* 4, 1211–1221

499 32 Banghart, M.R. *et al.* (2004) Light-activated ion channels for remote control of
500 neuronal firing. *Nature Neuroscience* 7, 1381–1386

501 33 Fortin, D.L. *et al.* (2011) Optogenetic photochemical control of designer K⁺
502 channels in mammalian neurons. *Journal of Neurophysiology* 106, 488–496

503 34 Sandoz, G. *et al.* (2012) Optical Control of Endogenous Proteins with a
504 Photoswitchable Conditional Subunit Reveals a Role for TREK1 in GABAB
505 Signaling. *Neuron* 74, 1005–1014

506 35 Volgraf, M. *et al.* (2005) Allosteric control of an ionotropic glutamate receptor
507 with an optical switch. *Nature Chemical Biology* 2, 47–52

508 36 Szobota, S. *et al.* (2007) Remote Control of Neuronal Activity with a Light-Gated
509 Glutamate Receptor. *Neuron* 54, 535–545

510 37 Berlin, S. *et al.* (2016) A family of photoswitchable NMDA receptors. *eLife* 5,
511 38 Levitz, J. *et al.* (2013) Optical control of metabotropic glutamate receptors. *Nature*
512 *Neuroscience* 16, 507–516

513 39 Tochitsky, I. *et al.* (2012) Optochemical control of genetically engineered neuronal

514 nicotinic acetylcholine receptors. *Nature Chemistry* 4, 105–111

515 40 Lin, W.-C. *et al.* (2014) Engineering a Light-Regulated GABAA Receptor for Optical
516 Control of Neural Inhibition. *ACS Chem. Biol.* 9, 1414–1419

517 41 Lin, W.-C. *et al.* (2015) A Comprehensive Optogenetic Pharmacology Toolkit for In
518 Vivo Control of GABA(A) Receptors and Synaptic Inhibition. *Neuron* 88, 879–891

519 42 Donthamsetti, P. *et al.* (2017) Optical Control of Dopamine Receptors Using a
520 Photoswitchable Tethered Inverse Agonist. *J. Am. Chem. Soc.* DOI:
521 10.1021/jacs.7b07659

522 43 Lemoine, D. *et al.* (2013) Optical control of an ion channel gate. *Proceedings of*
523 *the National Academy of Sciences* 110, 20813–20818

524 44 Caporale, N. *et al.* (2009) LiGluR Restores Visual Responses in Rodent Models of
525 Inherited Blindness. *Molecular Therapy* 19, 1212–1219

526 45 Levitz, J. *et al.* (2016) A Toolkit for Orthogonal and in vivo Optical Manipulation of
527 Ionotropic Glutamate Receptors. *Front. Mol. Neurosci.* 9, 2

528 46 Broichhagen, J. *et al.* (2015) Orthogonal Optical Control of a G Protein-Coupled
529 Receptor with a SNAP-Tethered Photochromic Ligand. *ACS Cent. Sci.* 1, 383–393

530 47 Levitz, J. *et al.* (2017) Dual optical control and mechanistic insights into
531 photoswitchable group II and III metabotropic glutamate receptors. *Proceedings*
532 *of the National Academy of Sciences* 114, E3546–E3554

533 48 Farrants, H. *et al.* (2018) SNAP-tagged nanobodies enable reversible optical
534 control of a G protein-coupled receptor via a remotely tethered photoswitchable
535 ligand. *ACS Chem. Biol.* DOI: 10.1021/acscchembio.8b00628

536 49 Berry, M.H. *et al.* (2018) Restoration of patterned vision with an engineered
537 photoactivatable G protein-coupled receptor. *Nature Communications* 2017, 1–
538 12

539 50 Tsai, Y.-H. *et al.* (2015) Selective, rapid and optically switchable regulation of
540 protein function in live mammalian cells. *Nature Chemistry* 7, 554–561

541 51 Kang, J.-Y. *et al.* (2013) In Vivo expression of a light-activatable potassium channel
542 using unnatural amino acids. *Neuron* 80, 358–370

543 52 Han, S. *et al.* (2017) Expanding the genetic code of *Mus musculus*. *Nature*
544 *Communications* 8, 1–7

545 53 Tian, L. *et al.* (2012) Selective esterase-ester pair for targeting small molecules

546 with cellular specificity. *Proceedings of the National Academy of Sciences* 109,
547 4756–4761

548 54 Gruber, T.D. *et al.* (2018) Cell-Specific Chemical Delivery Using a Selective
549 Nitroreductase-Nitroaryl Pair. *ACS Chem. Biol.* 13, 2888–2896

550 55 Yang, Y. *et al.* (2015) Cell type-specific pharmacology of NMDA receptors using
551 masked MK801. *eLife* 4, 9092

552 56 Chung, M.-K. *et al.* (2008) TRPV1 shows dynamic ionic selectivity during agonist
553 stimulation. *Nature Neuroscience* 11, 555–564

554 57 Khakh, B.S. *et al.* (1999) Neuronal P2X transmitter-gated cation channels change
555 their ion selectivity in seconds. *Nature Neuroscience* 2, 322–330

556 58 Binshtok, A.M. *et al.* (2007) Inhibition of nociceptors by TRPV1-mediated entry of
557 impermeant sodium channel blockers. *Nature* 449, 607–610

558 59 Kim, H.Y. *et al.* (2010) Selectively targeting pain in the trigeminal system. *Pain* 150,
559 29–40

560 60 Roberson, D.P. *et al.* (2011) Targeting of sodium channel blockers into nociceptors
561 to produce long-duration analgesia: a systematic study and review. *British Journal*
562 *of Pharmacology* 164, 48–58

563 61 Banghart, M.R. *et al.* (2009) Photochromic Blockers of Voltage-Gated Potassium
564 Channels. *Angew. Chem. Int. Ed. Engl.* 48, 9097–9101

565 62 Mourot, A. *et al.* (2012) Rapid optical control of nociception with an ion-channel
566 photoswitch. *Nature Methods* 9, 396–402

567 63 Mourot, A. *et al.* (2017) Understanding and improving photo-control of ion
568 channels in nociceptors with azobenzene photo-switches. *British Journal of*
569 *Pharmacology* 175, 2296–2311

570 64 Kim, Y.S. *et al.* (2014) Central Terminal Sensitization of TRPV1 by Descending
571 Serotonergic Facilitation Modulates Chronic Pain. *Neuron* 81, 873–887

572 65 Tochitsky, I. *et al.* (2014) Restoring Visual Function to Blind Mice with a
573 Photoswitch that Exploits Electrophysiological Remodeling of Retinal Ganglion
574 Cells. *Neuron* 81, 800–813

575 66 Tochitsky, I. *et al.* (2016) How Azobenzene Photoswitches Restore Visual
576 Responses to the Blind Retina. *Neuron* 92, 100–113

577 67 Mourot, A. *et al.* (2011) Tuning photochromic ion channel blockers. *ACS Chem.*

578 *Neurosci.* 2, 536–543

579 68 Chen, X. *et al.* (2015) The First Structure–Activity Relationship Studies for
580 Designer Receptors Exclusively Activated by Designer Drugs. *ACS Chem. Neurosci.*
581 6, 476–484

582 69 Gomez, J.L. *et al.* (2017) Chemogenetics revealed: DREADD occupancy and
583 activation via converted clozapine. *Science* 357, 503–507

584 70 Thompson, K.J. *et al.* (2018) DREADD Agonist 21 Is an Effective Agonist for
585 Muscarinic-Based DREADDs in Vitro and in Vivo. *ACS Pharmacology &*
586 *Translational Science* 1, 61–72

587 71 Magnus, C.J. *et al.* (2019) Ultrapotent chemogenetics for research and potential
588 clinical applications. *Science* 364,

589 72 Dong, M. *et al.* (2017) Near-Infrared Photoswitching of Azobenzenes under
590 Physiological Conditions. *J. Am. Chem. Soc.* 139, 13483–13486

591 73 Eldridge, M.A.G. *et al.* (2015) Chemogenetic disconnection of monkey
592 orbitofrontal and rhinal cortex reversibly disrupts reward value. *Nature*
593 *Neuroscience* 19, 37–39

594 74 Raper, J. *et al.* (2017) Metabolism and Distribution of Clozapine-N-oxide:
595 Implications for Nonhuman Primate Chemogenetics. *ACS Chem. Neurosci.* 8,
596 1570–1576

597 75 Weston, M. *et al.* (2019) Olanzapine: A potent agonist at the hM4D(Gi) DREADD
598 amenable to clinical translation of chemogenetics. *Sci Adv* 5, eaaw1567

599 76 Chen, X. and Wu, Y.-W. (2016) Selective chemical labeling of proteins. *Org.*
600 *Biomol. Chem.* 14, 5417–5439

601

602 **Glossary**

603

604 **Azobenzene**, chemical photoswitch that can be reversibly isomerized between an elongated
605 *trans* state and a twisted *cis* isomer with short (classically near-UV) and long (blue-green)
606 wavelengths of light, respectively.

607

608 **BOLT**, bioorthogonal ligand tethering. Ligand is conjugated to an UAA through click-chemistry.

609

610 **Bump-hole**, strategy based on the enlargement of binding sites (holes) in proteins (initially
611 enzymes) to make them selective to complementary “bumped” ligands.

612

613 **Click chemistry**, orthogonal bioconjugation reaction that is rapid, biocompatible and high
614 yielding.

615

616 **CM**, cyclopropylmethyl carboxyl. Masking group cleaved selectively by PLE.

617

618 **Cre/lox recombination**, genetic manipulation based on an enzyme, Cre recombinase, and its
619 recognition site, lox P, used for tissue-specific gene expression.

620

621 **DART**, drugs acutely restricted by tethering. Method for capturing drugs at the cell surface
622 using a HaloTag.

623

624 **DREADDs**, Designer Receptors Exclusively Activated by Designer Drugs. Engineered GPCRs
625 that exclusively respond to synthetic ligands.

626

627 **GPI anchor**, glycolipid (Glycosylphosphatidylinositol) that can be attached to the C-terminus
628 of a protein.

629

630 **His-tag**, tag made of 4 to 9 histidine residues (4 in the MAC technology) classically used for
631 purification of recombinant proteins.

632

633 **LOV domain**, light-oxygen voltage domain. Blue light sensor from algae, plants, bacteria and
634 fungi, used to control cellular responses with light.
635

636 **MAC**, metal complex–agonist conjugates. Bifunctional ligand containing a Ni²⁺-nitrilotriacetic
637 acid (Ni-NTA) moiety for selective coordination tethering to his-tagged receptors.
638

639 **Maleimide**, 1H-pyrrole-2,5-dione. Cysteine-reactive chemical group.
640

641 **NM**, 2-nitro-N-methylimidazolyl. Masking group selectively unmasked with NTR.
642

643 **NTR**, Nitroreductase from *E. Coli* used for selective reduction of NM groups.
644

645 **Opto-XR**, chimeric photocontrollable receptor engineered using opsins and the intracellular
646 loops or N-terminal tail of mammalian GPCRs.
647

648 **Orthogonal**, which does not interfere with native biological processes.
649

650 **PEG**, polyethylene glycol. Flexible polymer that is highly water soluble.
651

652 **PLE**, porcine liver esterase. Exogenous enzyme that efficiently and selectively hydrolyses CM
653 ester substrates.
654

655 **PORTL**, photoswitchable orthogonal remotely tethered ligand. Photoswitchable ligand
656 tethered to a protein or nanobody through SNAP- or CLIP-tag conjugation.
657

658 **PSAM/PSEM**, Synthetic protein (pharmacologically selective actuator module, PSAM) that is
659 selectively activated by synthetic ligands (pharmacologically selective effector molecules,
660 PSEMs).
661

662 **PTL**, photoswitchable tethered ligand. Thiol-reactive ligand incorporating a chemical
663 photoswitch, that photosensitizes cysteine-substituted receptors and ion channels.
664

665 **QAQ**, Quaternary-ammonium azobenzene quaternary-ammonium. Light-sensitive blocker of
666 voltage-gated potassium and sodium channels, used as a photoreversible local anesthetics.
667

668 **shRNAs**, short (or small) hairpin RNA used to silence gene expression.
669

670 **SNAP-, CLIP- and Halo-tags**, Protein-based self-labeling tags, catalyzing the formation of a
671 specific, covalent bond between a labeling molecule and a tag-fused protein of interest.
672

673 **Tethered**, covalently (irreversibly) anchored.
674

675 **Tet-on/off system**, tetracycline (Tet) approach for precise and reversible spatiotemporal
676 control of gene expression.
677

678 **Thiol**, side chain of the amino acid cysteine, which imparts reactivity to maleimides for ligand
679 tethering.
680

681 **UAA**, unnatural amino acid. Synthetic amino acid which can be incorporated in proteins using
682 the Amber stop codon technology.

683 **Figure legends**

684

685 **Figure 1 – Cell-specific neuropharmacology strategies.** A. Cell-specific pharmacology concept.
686 A drug (green) is delivered to the whole organism but targets only specific types of neurons in
687 the brain. The approach allows to evaluate the neurophysiological and behavioral
688 consequences of the manipulation of receptors in discrete circuits of the brain. B. Bump-hole
689 strategy. Top: the ligand (agonist or antagonist, green) acts on wild-type proteins. (Bottom
690 left) The engineered protein contains a “hole” in the binding pocket, while the synthetic ligand
691 (purple) contains a corresponding “bump”. The mutant protein is non-orthogonal because it
692 remains sensitive to the endogenous ligand (green). The orthogonal ligand acts specifically
693 and exclusively on the engineered protein. (Bottom right) Both the modified protein and the
694 synthetic ligand are orthogonal. C. Leftward shift in the concentration-response curve for the
695 synthetic ligand (purple) compared to the natural agonist or antagonist (green). D. Tethered-
696 ligand approaches developed for G-protein coupled receptors (GPCRs), ligand-gated (LGICs)
697 and voltage-gated ion channels (VGIC). (Left) The ligand is either embedded in the cell
698 membrane (membrane-tethered) or tethered to the receptor itself (receptor-tethered). E.
699 Intracellular delivery approaches. The drug is inactive in the extracellular space, and gets
700 active only after it has entered targeted cells. Color coding throughout figures A-E: native
701 proteins are shown in light grey and engineered ones in dark grey.

702

703 **Figure 2 – The receptor-ligand pair approach.** A. Designer Receptors Exclusively Activated by
704 Designer Drugs (DREADDs). DREADDs are orthologous receptor-ligand pairs made of a
705 modified human muscarinic receptor (hM), with mutations in transmembrane domains
706 (orange), that is insensitive to its natural agonist acetylcholine (ACh), but is exclusively
707 activated by a synthetic ligand (e.g. clozapine-N-oxide, CNO). B. The Pharmacologically
708 Selective Actuator Module/Effector Molecules (PSAM/PSEM) strategy: PSAM is an orthogonal,
709 engineered ligand binding domain (LBD) of the homopentameric $\alpha 7$ -nAChRs that is solely
710 activated by PSEM (and not ACh). Different ion pore domains (IPDs) can be spliced on the
711 PSAM allowing calcium, cation or chloride permeation. C. The Opto-XR approach: Opsin-GPCR
712 chimeras are made of the intracellular domains of mammalian GPCRs (such as $\beta 2$ - and $\alpha 1$ -
713 adrenergic receptors, grey) swapped on the transmembrane (TM) domain of mammalian
714 opsin (e.g. rhodopsin, blue). Opto-XRs are not sensitive to endogenous ligands (e.g.

715 norepinephrine, NE). They contain a retinal chromophore (blue) and enable the optical control
716 of intracellular signaling transduction. D. Zolpidem (pink) potentiates GABA signaling by
717 binding to GABA_ARs that contain the γ 2 subunit. Substitution of phenylalanine (F) 77 by
718 isoleucine (I) on γ 2 induces a loss of response to zolpidem. E. Mutation of the leucine residue
719 in position 9' (L9'), for instance to Alanine (A), leads to a "hypersensitive" nAChR that is
720 activated with subthreshold concentrations of the agonist nicotine.

721

722 **Figure 3 – The tethered ligand approach.** A. t-Toxins and t-Peptides are genetically-encoded
723 ligands permanently tethered to the cell surface through either a glycosylphosphatidylinositol
724 (GPI) anchor (depicted here) or a transmembrane domain (TM). B. Lumitoxin are chimeric
725 proteins composed of a TM, a light-oxygen-voltage (LOV) domain, a linker and a toxin (green).
726 In darkness, Lumitoxin blocks endogenous potassium channels at the cell surface, while
727 illumination with blue light unfolds LOV and relieves blockade. C. The Drug Acutely Restricted
728 by Tethering (DART) strategy is based on the expression of a TM anchor linked to a specific
729 self-labeling protein tag (e.g. HaloTag), allowing the capture of a specific ligand to the cell
730 surface. The ligand is composed of a HaloTag Ligand (HTL), a flexible linker (poly-ethylene
731 glycol, PEG) and a ligand (green). Conjugation results in a 100-fold increased concentration of
732 the ligand at the cell surface. D. Specific binding of a Metal complex-Agonist Conjugate (MAC)
733 to a His-Tagged GPCR, through coordination between the Ni²⁺-nitrilotriacetic acid (Ni-NTA)
734 group of the ligand and the His-Tag. E. Photoswitchable tethered ligands (PTLs) are composed
735 of a cysteine reactive group (maleimide, grey), a photosensitive azobenzene core (orange),
736 and a ligand (green). PTLs covalently attach to an engineered receptor that contains a single
737 cysteine substitution, near the ligand binding site, thereby affording reversible photocontrol.
738 F. Photoswitchable orthogonal remotely tethered ligands (PORTLs) are composed of a ligand,
739 a photoswitchable azobenzene molecule, a flexible linker and a benzylguanine (BG) or
740 benzylcytosine (BC) group for conjugation to SNAP- or CLIP-Tags, respectively.

741

742 **Figure 4: Intracellular delivery approaches.** A. The enzyme-prodrug pair approach relies on
743 the use of a masked prodrug, and an exogenous enzyme that converts the prodrug into an
744 active drug. B. The facilitated diffusion approach uses large ion channels such as TRPV1 or P2X
745 receptors for the selective entry of membrane-impermeant drugs. Here the drug is
746 photocontrollable, enabling on and off action at the target protein with two distinct

747 wavelengths of light.

748

749

750 Box 1: Bioconjugation technologies.

751 Bioconjugation reagents are used to link together a small chemical molecule (e.g. a ligand)
752 and a protein of interest (POI). Chemically tagging a protein with low toxicity and high
753 specificity in a complex cellular environment is a challenge. It requires genetic modification of
754 the POI, in order to incorporate a reactive group that will serve as a biorthogonal handle for
755 conjugation. Multiple strategies exist [76]. The smallest and least disruptive genetic
756 modification is the incorporation of a cysteine amino acid on the protein surface through site-
757 directed mutagenesis. Cysteines contain a thiol group that reacts efficiently, rapidly (minutes)
758 and with high selectivity with maleimide groups (Figure I) to form stable, covalent adducts
759 [76]. Cysteine has become the primary choice for site-specific modification of membrane
760 proteins because it is relatively low abundant, often engaged in disulfide bridges, and highly
761 nucleophilic at neutral pH [21]. Importantly, due the strong reductive environment of the
762 cytoplasm, cysteine-maleimide conjugation chemistry is restricted to extracellularly-
763 accessible sites on membrane proteins [21]. In addition, because cysteines are naturally
764 present on many endogenous proteins, novel bioconjugation techniques that work inside cells
765 and that are fully bio-orthogonal have been developed. This includes the use of unnatural
766 amino acids (UAA) that contain a double (alkene) or triple bond (alkyne) for bioconjugation
767 with tetrazine-containing ligands through click chemistry [50] (Figure I). Click-chemistry is
768 extremely popular for protein bioconjugation because it relies on chemical groups that are
769 highly selective toward each other -yet remain inert otherwise-, exhibits fast reaction kinetics
770 in aqueous media (minutes) and produces adducts that are very stable [76]. However, UAAs
771 must be incorporated into proteins through Amber codon suppression technology, which
772 remains challenging *in vivo* [52]. The other approaches for orthogonal labeling rely on larger
773 modifications of the POI, such as the incorporation of polypeptide tags. For instance, metal
774 chelation methods using poly-histidine tags (His-tag), which are classically used for protein
775 purification, have been used for non-covalent labeling with Ni-NTA ligands [31]. His-tags are
776 small (4-9 residues), conferring minimal disturbance to the protein, and label probes with high
777 efficiency and selectivity. Nevertheless, labeling is reversible and Ni is toxic to cells, hampering
778 *in vivo* use [76]. Finally, self-labeling domains such as SNAP-, CLIP- or HALO-tags use enzyme-

779 catalyzed reactions for irreversible conjugation of ligands to POI in live cells. The reaction is
780 highly biorthogonal, rapid, irreversible and works intracellularly with low concentration of
781 substrate (nanomolar range) [76], but requires fusion of the POI with a large protein domain
782 (>20 kDa) at the N- or C-terminus, which either is prohibited (as with nAChRs or GABA_ARs for
783 instance) or may affect POI function.

784

785 Box1 Figure I. Representative reactive groups for protein-ligand bioconjugation.

786

787

788

Highlights

Chemogenetic technologies that combine the speed of pharmacology with the cellular precision of genetics are emerging, enabling acute control of neuronal receptors with circuit specificity.

Targeting drugs to specific neuronal types usually requires genetic manipulation of either the target protein or the target cell.

In vivo implementation of these technologies allows unprecedented control brain of circuits at the molecular level, and help unambiguously link the activity of specific receptors to behavioral functions.

Outstanding questions box

Is multiplexing possible? Only some of the methods described here allow for multiplexed interrogation across cell- (DREADDs, PSAM, DART) and receptor-types (PORTL). Notably, CLIP-mGluR2 and SNAP-mGluR7 expressed in the same cell could be labeled and manipulated with orthogonal reactivity and wavelengths, respectively [41]. Nevertheless, novel approaches for concurrent delivery of two or more drugs to distinct cellular populations are needed.

Can DART be made photo-reversible? One current limitation of the DART technology is its slow reversal. In principle, adding a photo-isomerizable linker could help accelerate the off rate, as in the PORTL approach. However, DART and PORTL have two major differences: ligand/receptor stoichiometry and fixed vs. variable distance between the receptor and the anchor. It will be interesting to determine whether DART can be made photo-controllable.

Can fully bio-orthogonal groups be developed for tethered ligands? Most of the functional groups described in this review are not fully orthogonal, causing non-specific labeling in live cells. Others are too large (SNAP, CLIP...) and may affect protein function. Some groups are too lipophilic and have limited bioavailability. And most of them cannot pass the blood brain barrier and therefore have to be delivered locally into the brain. Hence, numerous challenges remain in bio-orthogonal chemistry in live cells.

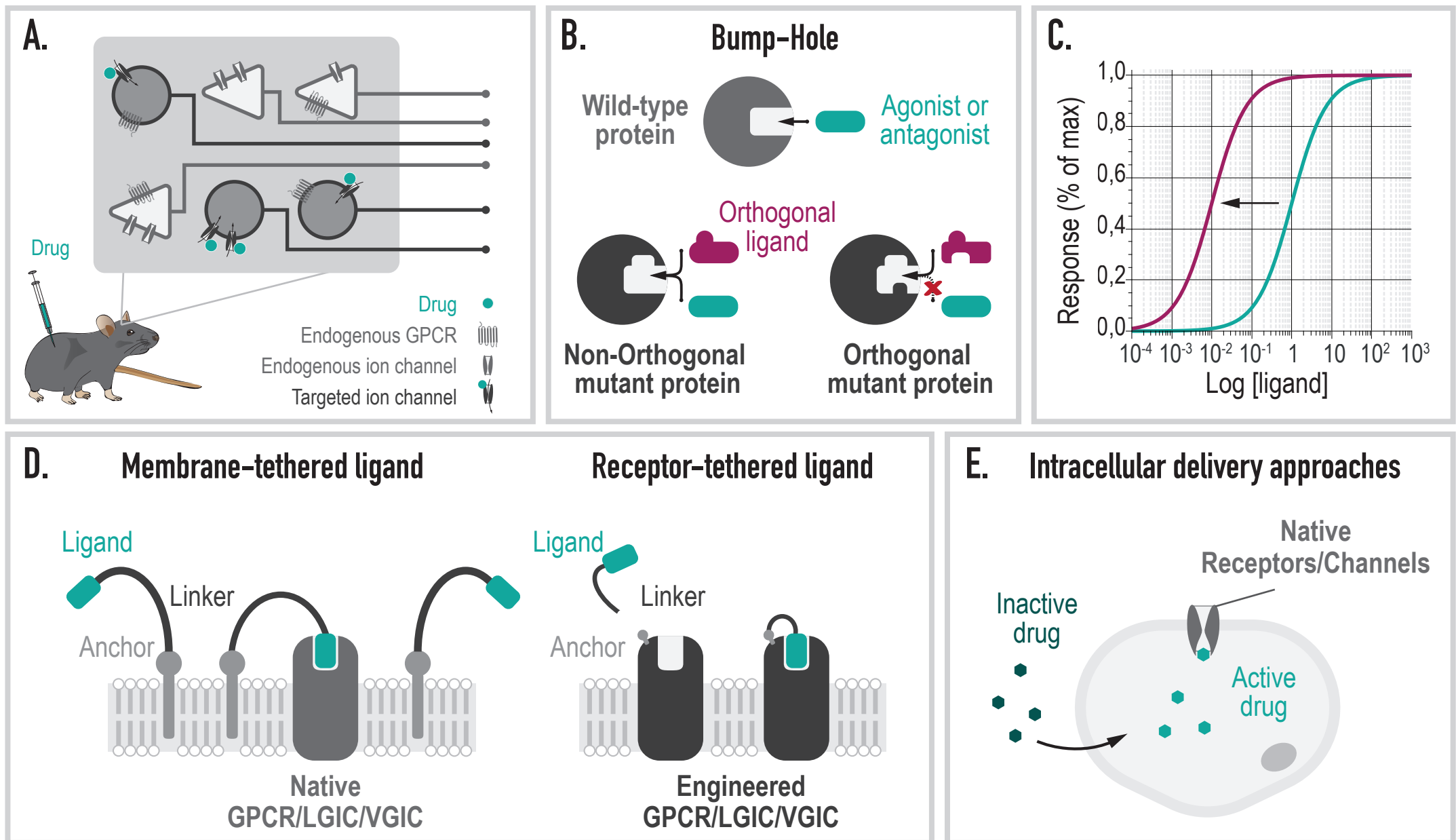
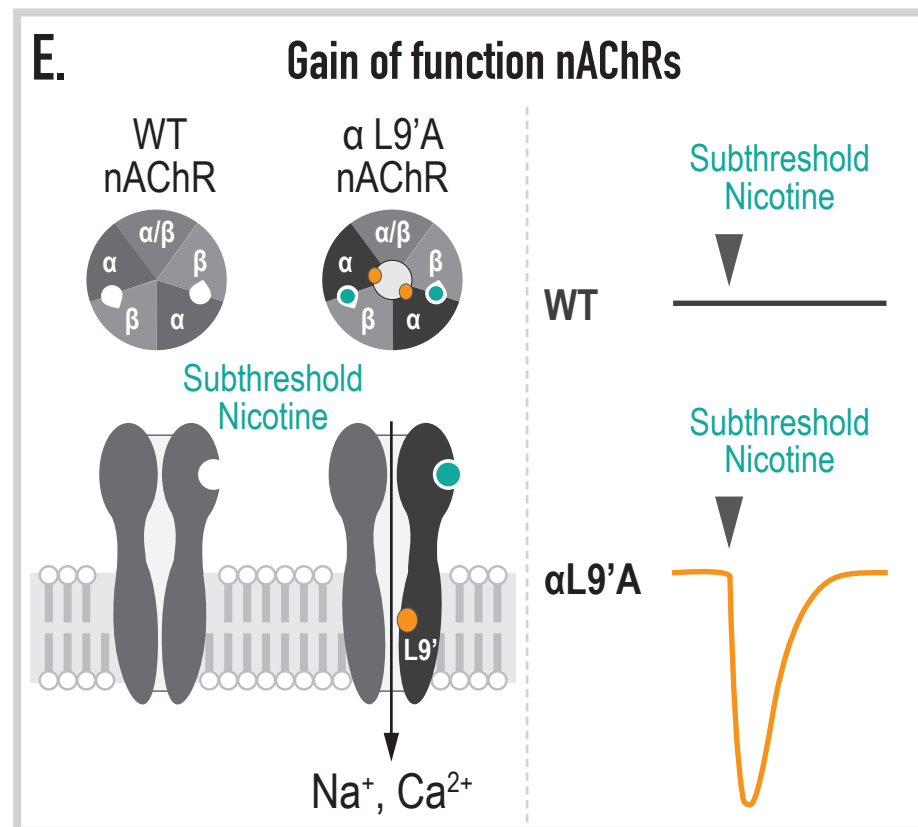
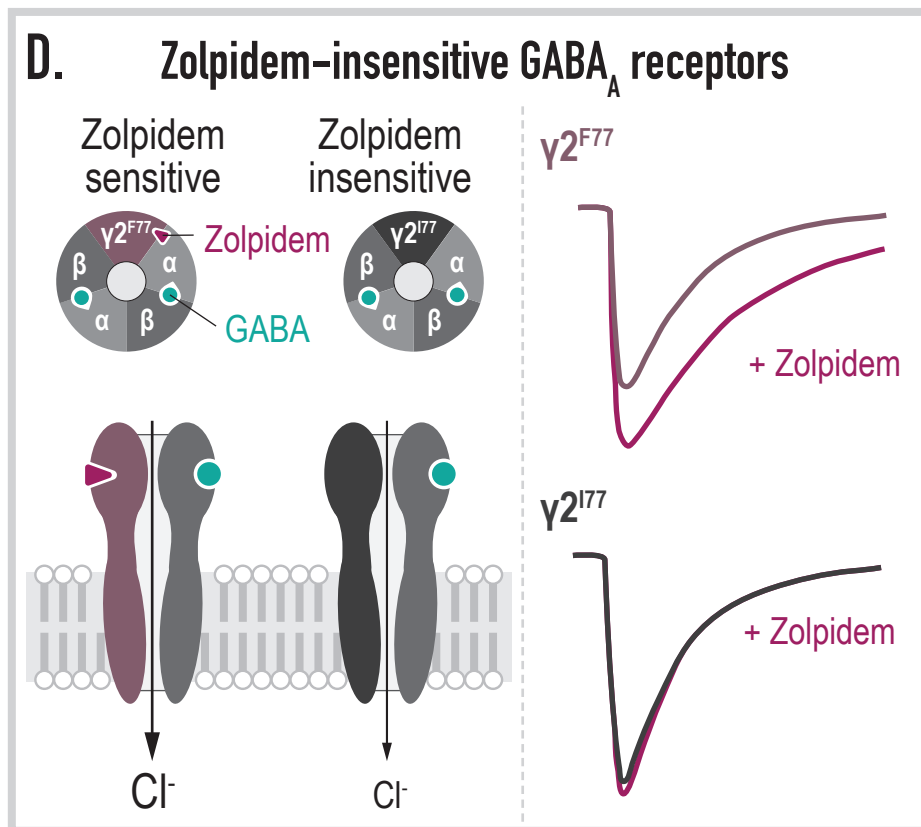
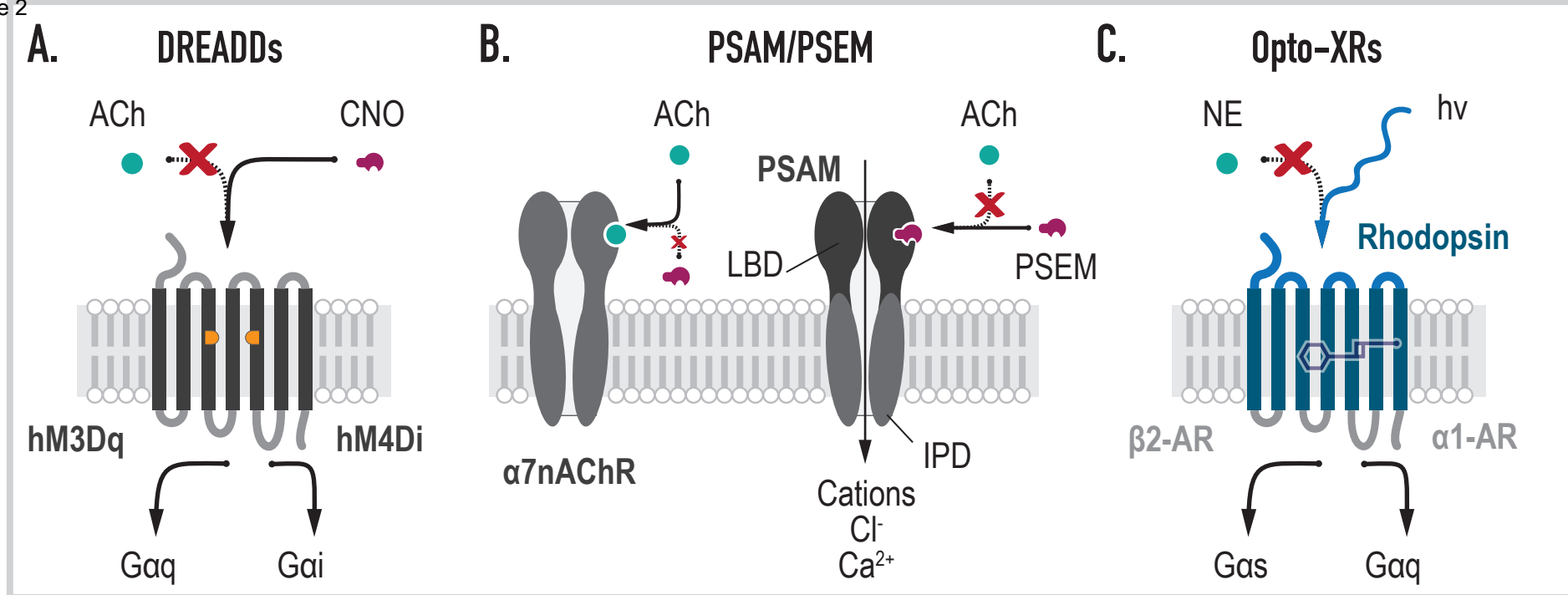


FIGURE 1



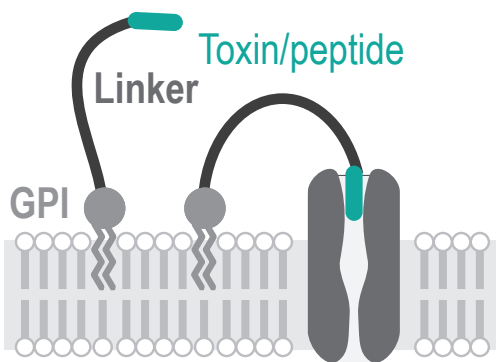
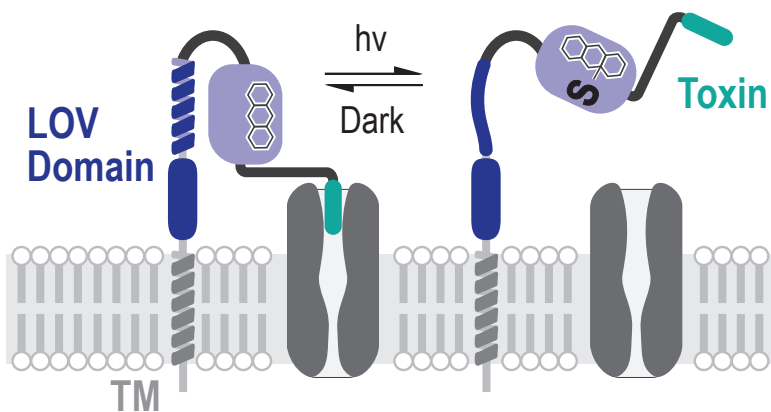
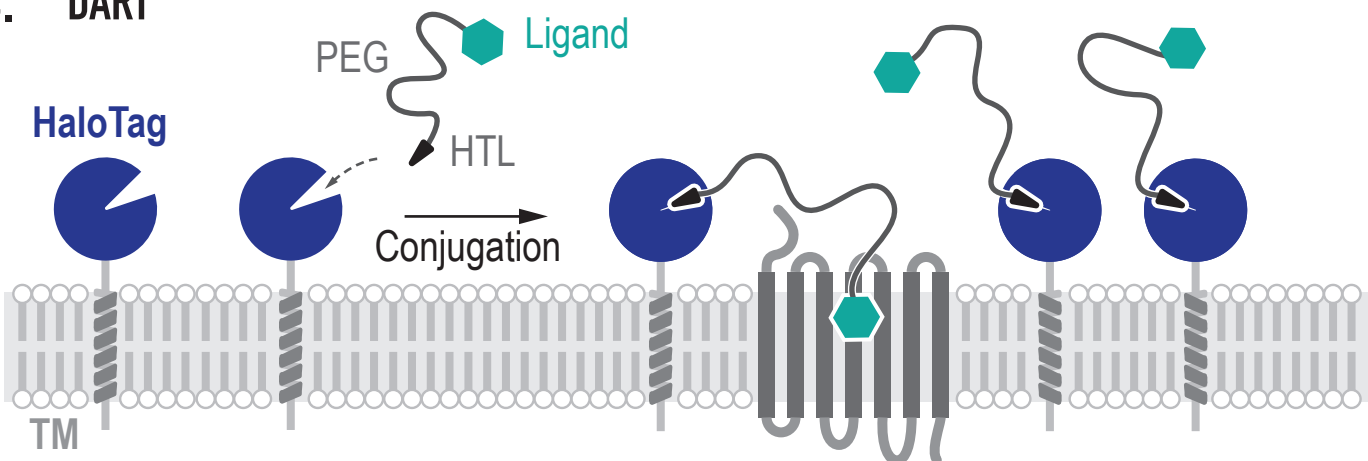
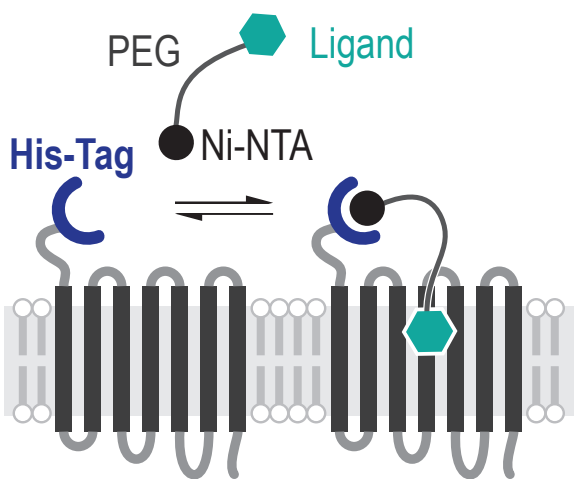
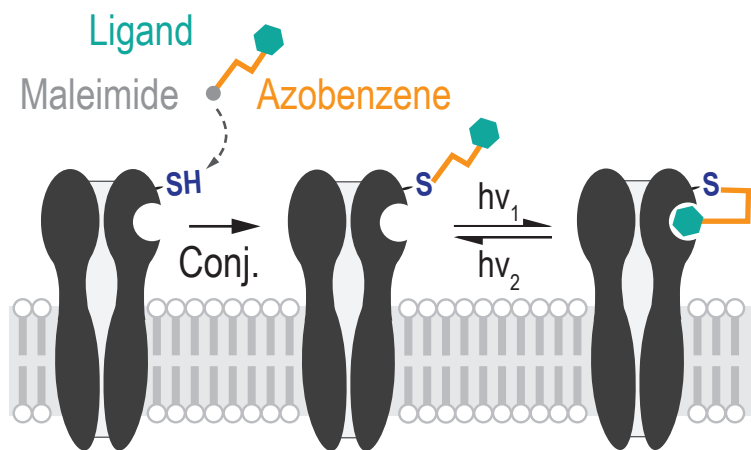
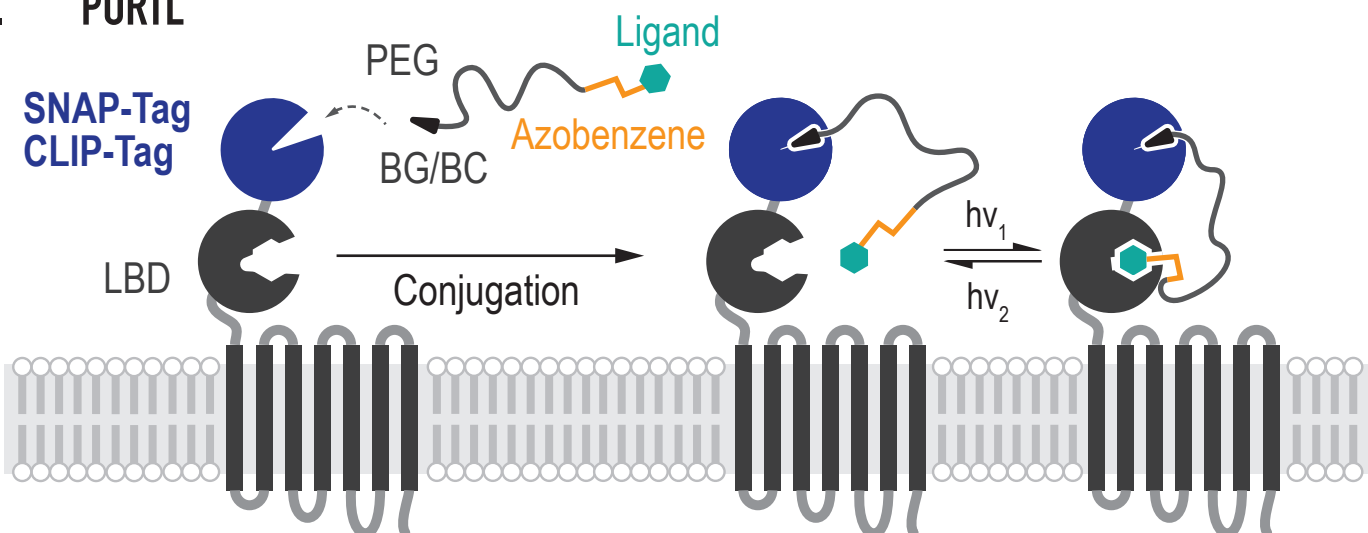
A. t-Toxins/t-Peptides**B. Lumitoxin****C. DART****D. MAC****E. PTL****F. PORTL**

FIGURE 4

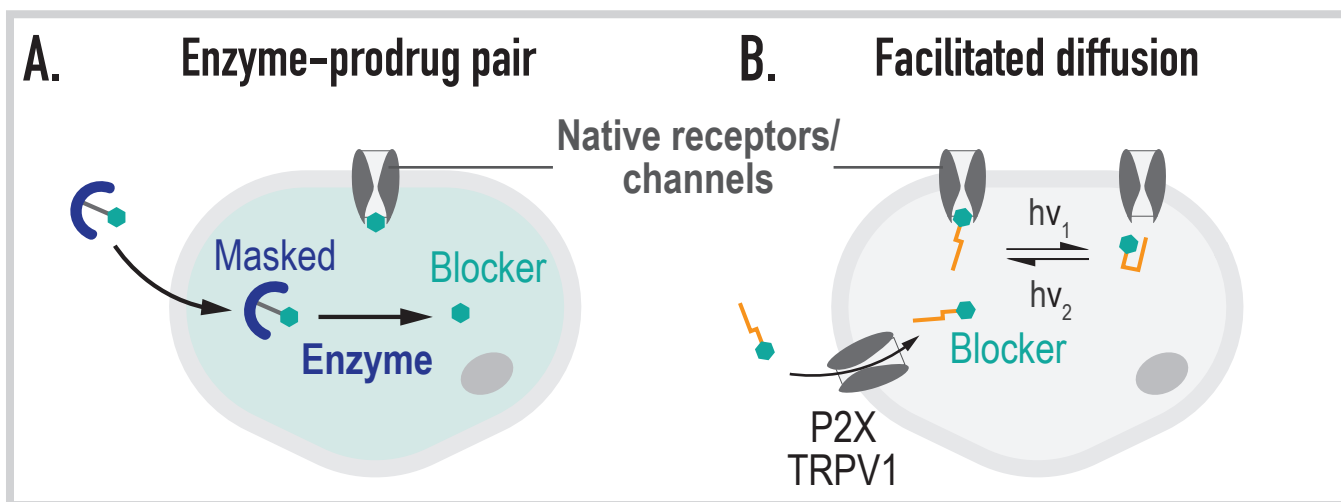


FIGURE - Box 1

