

Cover Page



Universiteit Leiden

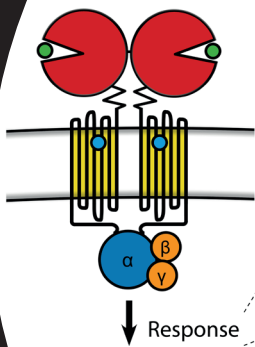


The handle <http://hdl.handle.net/1887/65384> holds various files of this Leiden University dissertation.

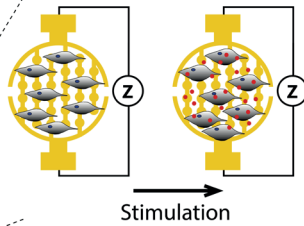
**Author:** Doornbos, M.L.J.

**Title:** Towards improved drug action : target binding kinetics and functional efficacy at the mGlu2 receptor

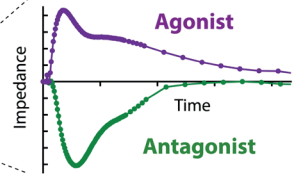
**Issue Date:** 2018-09-12



### mGlu<sub>2</sub> receptor pharmacology



**label-free biosensor**



Allosteric modulation  
Constitutive activity  
Inverse agonism

## CHAPTER 6

### Constitutive activity of the metabotropic glutamate receptor 2 explored with a whole-cell label-free biosensor

*Maarten L J Doornbos, Ilse Van der Linden,  
Liesbeth Vereyken, Gary Tresadern, Adriaan P  
IJzerman, Hilde Lavreysen & Laura H Heitman*

*Biochemical Pharmacology 152 (2018) 201–210.  
doi:10.1016/j.bcp.2018.03.026.*





## ABSTRACT

Label-free cellular assays using a biosensor provide new opportunities for studying G protein-coupled receptor (GPCR) signaling. As opposed to conventional *in vitro* assays, integrated receptor-mediated cellular responses are determined in real-time rather than a single downstream signaling pathway. In this study, we examined the potential of a label-free whole cell impedance-based biosensor system (i.e. xCELLigence) to study the pharmacology of one GPCR in particular, the mGlu<sub>2</sub> receptor. This receptor is a target for the treatment of several psychiatric diseases such as schizophrenia and depression.

After optimization of assay conditions to prevent interference of endogenous glutamate in the culture medium, detailed pharmacological assessments were performed. Concentration-response curves showed a concentration-dependent increase in impedance for agonists and positive allosteric modulators, whereas receptor inhibition by an antagonist or negative allosteric modulator resulted in a concentration-dependent decrease in cellular impedance. Interestingly, constitutive receptor activity was observed that was decreased by LY341495, which therefore behaved as an inverse agonist here, a property that was heretofore unappreciated. This was confirmed by concentration-dependent modulation of LY341495 potency and efficacy by allosteric modulators.

In summary, the use of the xCELLigence system to study mGlu<sub>2</sub> receptor pharmacology was validated. This is the first class C GPCR to be characterized extensively by such method, opening new avenues to study receptor pharmacology including inverse agonism and demonstrating its value for future drug discovery efforts of mGlu receptors as well as other GPCRs.

## INTRODUCTION

Traditionally, drug discovery at G protein-coupled receptors (GPCRs) has been based on screening drug candidates using functional *in vitro* endpoint-based assays in which the ability of a compound to activate or inhibit a certain pathway is determined. Over the last decade on the other hand the use of label-free cellular assays has greatly increased.<sup>1,2</sup> These assays, typically using a biosensor, measure cellular responses upon ligand stimulation, which result in morphological changes of the whole cell.<sup>3</sup> Thereby some of the caveats of traditional endpoint assays are circumvented: no labels (e.g. radioactive, fluorescent) or reporter genes are required and measurements can be performed continuously.<sup>4</sup> Cell types used include recombinant cell lines, cell lines endogenously expressing the target of interest and even patient-derived cells.<sup>5</sup> Label-free assays used to study GPCR responses are mostly based on measurement of changes in cell morphology either optically, such as EPIC (Corning Inc.) or by changes in impedance, such as xCELLigence (ACEA Biosciences).<sup>1,6</sup> These systems have proven valuable in studying GPCR pharmacology in different cell lines.<sup>7-9</sup>

Being a presynaptic regulator of glutamate release, the mGlu<sub>2</sub> receptor has been of great interest in drug discovery over the last decade. This receptor, a class C GPCR, has emerged as therapeutic target for various psychiatric diseases amongst which schizophrenia, depression and anxiety, which are characterized by glutamatergic dysfunction.<sup>10,11</sup> A variety of glutamate-like agonists that can dampen glutamate hyperfunction was developed, of which LY2140023 of Eli Lilly, a prodrug of LY404039 showed improvement in positive and negative symptoms in schizophrenic patients, which could not be confirmed in later clinical studies.<sup>12,13</sup> Inhibition of the mGlu<sub>2</sub> receptor can be beneficial for glutamate hypofunction in depression, and when considering the orthosteric binding site antagonist LY341495 has been the most studied for this purpose.<sup>14,15</sup> Since the orthosteric site is highly conserved<sup>14,15</sup> among the mGlu receptor subtypes and medicinal chemistry of orthosteric ligands is constrained to hydrophilic glutamate derivatives, drug development efforts later shifted to allosteric modulators for the mGlu<sub>2</sub> receptor, which have been shown to bind in a less evolutionary conserved binding site within the transmembrane domain.<sup>16-18</sup> This allosteric binding site is more hydrophobic and allows more chemical diversity.<sup>19</sup> Therefore, subtype selectivity is obtained relatively easier and allosteric modulators are more prone to cross the blood brain barrier due their increased lipophilicity. Allosteric modulators enhance or inhibit the affinity and/or efficacy of the endogenous agonist glutamate and some positive allosteric modulators (PAMs) also show intrinsic efficacy, referred to as PAM agonism.<sup>20</sup> Reference PAMs in the field include JNJ-40068782,<sup>21</sup> BINA<sup>22</sup> and JNJ-46281222.<sup>23</sup> Two PAMs entered clinical trials, AZD8529 of AstraZeneca and JNJ-40411813 (also known as ADX71149) from Janssen/Addex.<sup>24-29</sup> A number of mGlu<sub>2</sub> negative allosteric modulators (NAMs) have been characterized *in vivo*, including a recent series

of NAMs from Janssen and RO4491533 and decoglutrant from Roche, of which the latter also advanced into clinical trials.<sup>30–32</sup> Taken together, discovery efforts have resulted in a great diversity of selective and high affinity mGlu<sub>2</sub> ligands, but no compounds have successfully passed clinical evaluation.

To increase the understanding on ligand-induced mGlu<sub>2</sub> responses, we evaluated in this study the use of the label-free impedance-based xCELLigence system to study the pharmacology of the mGlu<sub>2</sub> receptor *in vitro*. A benefit of this biosensor is that experiments are performed under more relevant conditions than most traditional assays (i.e. living cells at 37°C in culture medium). After optimization of pre-treatment conditions to reduce the concentration of endogenous glutamate in the assay medium, responses of an agonist, antagonist, PAM and NAM were studied. Furthermore, we evaluated constitutive receptor activity by using antagonist/inverse agonist and NAM pre-treatment experiments. Finally, the effects of a PAM or NAM on agonist efficacy were studied. Taken together, biosensor-based label-free systems are helpful in studying (novel) mGlu<sub>2</sub> pharmacology in a more physiologically relevant environment. Our studies may be equally relevant for other class C GPCRs.

## MATERIALS AND METHODS

### Materials

LY354740, RO4491533 and JNJ-46281222 were synthesized at Janssen Research and Development (Toledo, Spain). LY341495 was obtained from Tocris BioScience (Bristol, UK). Benzoylchloride, Dulbecco's modified Eagle's medium (DMEM), glutamate, glutamine, glutamate-d5 standards, glutamate-pyruvate transaminase (GPT), pertussis toxin (PTX) and sodium pyruvate were from Sigma-Aldrich (St. Louis, MO, USA). Penicillin, streptomycin, L-Proline and G418 were obtained from Duchefa Biochemie (Haarlem, The Netherlands). Fetal calf serum (FCS) was from Biowest (Nuaille, France). PET E-plates 16 and 96 for the xCELLigence DP and SP system (ACEA Biosciences, San Diego, CA, USA) were obtained from Bioké (Leiden, the Netherlands). Chinese hamster ovary cells (CHO-K1, CCL-61) were from ATCC (Rockville, MD, USA). CHO-K1 cells stably expressing the hmGlu<sub>2</sub> receptor (CHO-K1\_hmGlu<sub>2</sub>) were from Janssen Research and Development (Beerse, Belgium). Acetonitrile ULC/MS-grade was purchased from Biosolve (Valkenswaard, The Netherlands). Formic acid 98–100% and disodium tetraborate decahydrate were obtained from Merck (Darmstadt, Germany). High purity water was obtained with a Milli-Q Reference Ultrapure Water Purification System (Merck Millipore, Billerica, MA, USA). Other chemicals were of analytical grade and from standard commercial sources.

## Cell culture

CHO-K1\_hmGlu2 cells were grown in DMEM supplemented with 10% (v/v) FCS, 200 IU·mL<sup>-1</sup> penicillin, 200 µg·mL<sup>-1</sup> streptomycin, 30.5 µg·mL<sup>-1</sup> L-proline and 400 µg·mL<sup>-1</sup> G418 at 37°C and 5% CO<sub>2</sub>. CHO-K1 WT cells were cultured in the same medium without G418.

## Analysis of glutamate concentration

### *Preparation of stock solutions and curves*

As glutamate is present in the culture medium as an endogenous entity, a calibration curve had to be prepared in an artificial matrix, for which demineralised water was used. Therefore, a quality check was performed to validate quantification of the samples with a standard addition step (a known amount of glutamate is spiked to a sample). The calibration curve was prepared in a range of 0.010 – 50 µg/ml, starting from a stock solution of 100 µg/ml glutamate in water. Glutamate-d5 was used as a stable isotope labelled internal standard (STIL).

### *Sample preparation*

Glutamate was quantified after derivatization with benzoylchloride. 20µL medium was transferred to a sample tube, subsequently 20µL of the calibration curve in water was added followed by 20µL of STIL Glu-d5 and 20µL of NaBorate solution (100mM, pH 8). For derivatization, 40µl benzoylchloride (3% v/v in acetonitrile) was transferred to the sample tubes, after which samples were incubated for 15 min at 50°C and subsequently cooled to room temperature for 10 min. Finally, 200µL 0.1% formic acid was added. Samples were vortexed and centrifuged for 3min at 6000g, after which the supernatant was analyzed.

### *Liquid chromatography – mass spectrometry*

Chromatographic separation was performed with an Acquity UPLC system (Waters, Millford, Boston, USA). Injections of 2 µL were made on an Acquity UPLC BEH C18 2.1 x 50 mm (1.7 µm particles) column held at 55°C at a flow rate of 0.400 ml/min. Chromatographic elution started isocratically at 2% solvent B (acetonitrile) and 98% solvent A (0.1% formic acid) for 0.2 min. A subsequent linear gradient to 30% B in 1.8 min, followed by a wash step (0.2 min at 98% solvent B) and 0.8 min equilibration time at 2%B resulted in a total run time of 3 min/injection.

Instrument parameters were optimized by injecting a glutamate standard solution (2 ng/ml in 0.1% formic acid/acetonitrile, v/v; 80/20) at a flow rate of 10 µl/min. The following source parameters were used: source temperature 150°C, desolvation temperature 450°C, capillary 2.9kV, sampling cone 30V, source offset 50V, cone gas 150 L/h, desolvation gas 900 L/h, collision gas flow 0.18 ml/min and nebulizer gas 6 ml/min. Glutamate was analyzed in the positive ion mode with electrospray ionization and detected by multiple reaction monitoring (MRM) (collision energy 20 eV and dwell time 75 ms) on a triple quad Xevo TQ-s system (Waters, Manchester, UK), monitoring the channels of  $m/z$  252.1 → 105.1 (quantifier) and  $m/z$  252.1 → 130.1 (qualifier), respectively. The MRM transition monitored for the STIL Glu-d5 is  $m/z$  257.1 → 105.1. During method optimization, special consideration was given to the chroma-



tographic separation of glutamate and glutamine. The incubation medium has an excessive amount of glutamine present and it is known that glutamine, with a MW 1 Da lower than glutamate, gives crosstalk in the MRM channel of glutamate. Therefore, glutamine was also monitored, at  $m/z$  251.1  $\rightarrow$  105.1 as a qualifier. Quantitative values were obtained by relating chromatographic peak areas to those derived from separately run calibration standards as described above. Calibration curves were plotted using a non-weighted log-log linear regression.

### Label-free whole-cell assays

Label-free whole-cell assays were performed using the xCELLigence real-time cell analyzer (RTCA) system<sup>3,33</sup> as previously described.<sup>7</sup> The system measures whole-cell responses based on changes in electrical impedance generated by adherence of cells to gold-coated electrodes at the bottom of microelectronic E-plates. Relative changes in impedance ( $Z$ ) are recorded continuously and displayed in the dimensionless parameter Cell Index (CI), which is defined as  $(Z_i - Z_0) \Omega / 15\Omega$ .  $Z_i$  is the impedance at a given time and  $Z_0$  is the baseline impedance measured at the start of the experiment in the absence of cells.

$Z_0$  was measured after adding 45  $\mu$ l, or in the case of pre-incubation experiments 40  $\mu$ l, culture medium per well in 16 or 96 well E-plates. 50  $\mu$ l of cell suspension was added to the plate containing 40,000 cells per well. After resting at room temperature for 30 minutes, E-plates were mounted in the recording station within a humidified 37°C, 5% CO<sub>2</sub> incubator. Subsequently, impedance was measured overnight every 15 minutes. To remove endogenous glutamate, refreshment of culture medium by culture medium or serum-free culture medium with GPT (3 U/ml) and additional pyruvate (3 mM) was performed 3 hours before stimulation unless stated otherwise. For evaluation of constitutive receptor activity, pre-incubation with antagonist LY341495 or NAM RO4491533 was performed 1 hour before stimulation. After 19 hours, cells were stimulated with increasing concentrations of ligand (i.e. agonist, antagonist, PAM or NAM). Final well volumes after addition of compounds were 100  $\mu$ l in all cases. DMSO concentrations were constant between wells and were  $\leq$  0.1%. For inhibition of G $\alpha_i$  signaling, cells were seeded in culture medium containing PTX (300 ng/ml) when indicated. PTX concentrations were kept constant also after medium refreshment.

### Data analysis

RTCA software 2.0 (ACEA Biosciences) was used to obtain the experimental data. All analyses were performed using Prism 7.00 (GraphPad software, San Diego, CA, USA). Ligand responses were normalized to  $\Delta$  cell index ( $\Delta$ CI) after subtracting baseline (vehicle control) to correct for ligand-independent effects. Maximum or minimum peak responses were considered as the highest or lowest level of  $\Delta$ CI within 60 min after compound stimulation and were used for bar graphs and concentration-response curves. pEC<sub>50</sub> and pIC<sub>50</sub> values were obtained using non-linear regression curve fitting into a sigmoidal dose-response curve with variable

slope. Data shown are the mean  $\pm$  SEM of at least three individual experiments performed in duplicate. Statistical analyses were performed as indicated. If p-values were below 0.05, observed differences were considered statistically significant.

## RESULTS AND DISCUSSION

### **Serum-free assay medium with GPT resulted in lowest levels of endogenous glutamate**

One of the benefits of the xCELLigence biosensor is that experiments can be performed under more relevant conditions than most traditional assays (i.e. living cells at 37°C in culture medium). However, endogenous glutamate is often found in culture medium and is also continuously produced by cells.<sup>34</sup> As high levels of glutamate will interfere with functional responses by other mGlu<sub>2</sub> receptor agonists, we first determined the concentration of endogenous glutamate in culture medium using HPLC analysis, which was found to be  $78 \pm 2.0 \mu\text{M}$  (Table 1). Since the potency of glutamate to activate the mGlu<sub>2</sub> receptor is around  $10 \mu\text{M}$ , this concentration is capable to activate the mGlu<sub>2</sub> receptor to a high level as shown in **chapter 2 and 6** and earlier by Pin *et al.* (1999).<sup>35</sup> Hence, we aimed to reduce the concentration of endogenous glutamate in the culture medium. For this purpose, glutamate-pyruvate transaminase (GPT; 3 U/ml) was added in the presence of additional pyruvate (3 mM), a procedure commonly used in the field of mGlu receptors, e.g.<sup>36,37</sup> This treatment led to an almost 4-fold lower concentration of glutamate in the culture medium:  $23 \pm 0.09 \mu\text{M}$ . At this concentration, glutamate is still able to activate the receptor over 50% and will thus significantly interfere with the functional readout. Next, we switched to serum-free medium, which we determined to contain only  $0.22 \pm 0.005 \mu\text{M}$  endogenous glutamate, indicating that the fetal calf serum (FCS) present in the culture medium was the main source of glutamate.

Importantly, when seeded in serum-free medium, cells did not attach to the bottom of the wells, did not proliferate and therefore did not show any remarkable level of impedance (data not shown). This clearly indicated that cells required FCS for growth and proliferation. Therefore, serum-free medium was added to the wells by medium refreshment three hours before stimulation only. Of note, during these first three hours of the serum-free medium being on the cells, the concentration of glutamate increased to  $13 \pm 0.47 \mu\text{M}$  at the time of stimulation (Table 1). Therefore, GPT and pyruvate were added to this serum-free assay medium, resulting in a stable concentration of endogenous glutamate during the signaling read-out of 1 hour (i.e. from  $1.6 \pm 0.09 \mu\text{M}$  at the moment of stimulation to  $2.3 \pm 0.62 \mu\text{M}$  two hours after stimulation, Table 1). This residual level of endogenous glutamate only slightly activates the receptor to a maximum level of approximately 10%, leaving a large experimental window for further (exogenous) agonist-induced receptor signaling studies.

**Table 1.** Glutamate concentrations ( $\mu\text{M}$ ) in culture medium or serum-free medium with and without addition of GPT (3U / ml) and pyruvate (3 mM). Medium was added to the cells at the time of medium refreshment (-3 hrs).

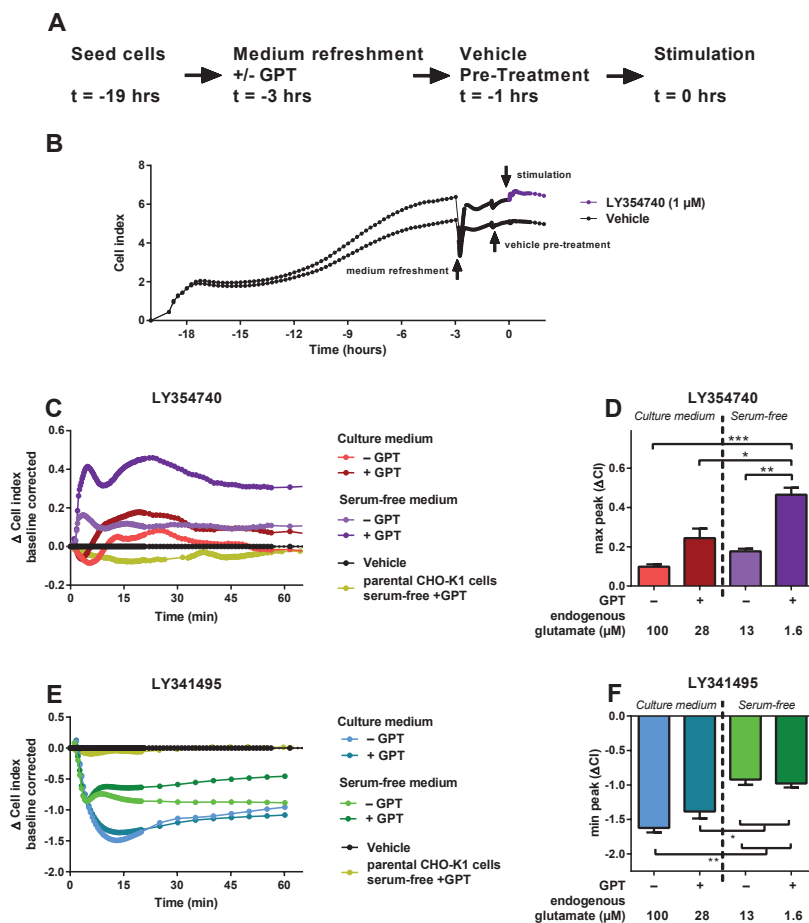
Time of:	Time from stimulation (hrs)	Culture medium		Serum-free medium	
		- GPT	+ GPT	- GPT	+ GPT
medium refreshment	-3	78 $\pm$ 2.0	23 $\pm$ 0.09	0.22 $\pm$ 0.005	0.098 $\pm$ 0.004
	-2.5	83 $\pm$ 1.6	23 $\pm$ 0.58	3.7 $\pm$ 0.20	1.2 $\pm$ 0.09
pre-treatment	-1	88 $\pm$ 1.3	25 $\pm$ 0.90	9.8 $\pm$ 0.09	1.2 $\pm$ 0.10
stimulation	0	100 $\pm$ 3.0	28 $\pm$ 1.1	13 $\pm$ 0.47	1.6 $\pm$ 0.09
	2	100 $\pm$ 9.4	33 $\pm$ 1.9	17 $\pm$ 2.1	2.3 $\pm$ 0.62

Data are shown as mean  $\pm$  SEM of at least three individual experiments performed in duplicate.

### Endogenous glutamate reduced agonist yet enhanced antagonist responses

The mGlu<sub>2</sub> receptor-mediated signaling was monitored on the xCELLigence RTCA system. In the field of class C GPCRs, this technique was never characterized extensively, yet it was used as a tool in two studies: Scandroglio *et al.* (2010)<sup>38</sup> presented a small proof of concept study on the mGlu<sub>1</sub> receptor and we reported on the mGlu<sub>2</sub> receptor using the xCELLigence as a tool to assess the effect of binding kinetics on functional efficacy of mGlu<sub>2</sub> PAMs in **chapter 3 and 4**. Here, CHO-K1<sub>hmGlu<sub>2</sub></sub> cells stably expressing the hmGlu<sub>2</sub> receptor were used. 40,000 cells/well were seeded in culture medium 19 hours prior to stimulation (Fig. 1A). The cells adhered well to the bottom of the wells on the gold-coated electrodes, which is essential for sufficient measurements of impedance.<sup>39</sup> Therefore no additional well coatings had to be used. Overnight proliferation generally led to cell indices (CI) between 3 and 5 (Fig. 1B for two representative traces), dependent on cell passage number and confluency.

As discussed above, the concentration of endogenous glutamate varied between different pre-treatment conditions (Table 1). To assess how this affected the response of an mGlu<sub>2</sub> receptor agonist or antagonist, responses of a single 1  $\mu\text{M}$  concentration of LY354740 and LY341495 were obtained, respectively. This concentration was chosen such that it is well above the respective potencies of the two ligands. The traces of the agonist LY354740 at 1  $\mu\text{M}$  were always “positive”, inducing an increase in Cell Index and thus impedance (Fig. 1C,D). The responses after different pre-treatment conditions varied greatly. When using normal culture medium containing a high concentration of endogenous glutamate at the time of stimulation (100  $\pm$  3.0  $\mu\text{M}$ ), a small LY354740 response was observed, with peaks at an average maximum  $\Delta\text{CI}$  level of 0.098  $\pm$  0.012 (Fig. 1D). In the presence of GPT and pyruvate the glutamate concen-



**Figure 1.** Agonist LY354740 and antagonist LY341495-induced responses in the presence of different concentrations of endogenous glutamate. A) Set-up of experiments. B) Typical growth curve of CHO-K1 cells stably expressing the mGlu<sub>2</sub> receptor (40,000 cells/well). 3 hours prior to stimulation culture medium was replaced by serum-free medium containing GPT (3 U/ml) and additional pyruvate (3 mM). Cells were stimulated with LY354740 (1  $\mu$ M). Serum-free medium with 0.025% DMSO was used as vehicle control. C) Responses induced by 1  $\mu$ M LY354740 after different pre-treatment conditions and the response of 1  $\mu$ M LY354740 on CHO-K1 WT cells three hours after replacement of culture medium by serum-free medium containing GPT. D) Maximum peak values induced by 1  $\mu$ M LY354740 in the presence of different concentrations of endogenous glutamate as presented in table 1. E) Responses induced by 1  $\mu$ M LY341495 after different pre-treatment conditions and the response of 1  $\mu$ M LY341495 on CHO-K1 WT cells three hours after replacement of culture medium by serum-free medium containing GPT. F) Maximum peak values induced by 1  $\mu$ M LY341495 in the presence of different concentrations of endogenous glutamate as presented in table 1. All xCELLigence traces are from representative experiments performed in duplicate. Bar graphs represent mean  $\pm$  SEM of at least three individual experiments performed in duplicate. Statistical analyses were performed using one-way ANOVA with Tukey's post-test. \*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ .

tration was reduced to  $28 \pm 1.1 \mu\text{M}$  at stimulation, resulting in an increased LY354740 response with maximum peaks of  $0.24 \pm 0.05 \Delta\text{CI}$ . This response reached a similar maximum level as when culture medium was replaced by serum-free medium, although the LY354740 response was more prompt in that case (Fig. 1C). The highest and significantly increased LY354740 response was obtained using medium refreshment with serum-free medium containing GPT and pyruvate, which contained  $1.6 \pm 0.09 \mu\text{M}$  endogenous glutamate at the time of stimulation, leading to significantly increased maximum peaks of  $0.47 \pm 0.04 \Delta\text{CI}$ . Even in the presence of a high concentration of endogenous glutamate, LY354740 was still able to induce responses (Fig. 1C,D), which exemplified the sensitivity of the xCELLigence system, registering very small ligand-induced responses.

In contrast to the positive LY354740 responses,  $1 \mu\text{M}$  antagonist LY341495 induced opposite negative responses in Cell Index (Fig. 1E). As for the agonist LY354740, the peak level (i.e. minimum peak in case of LY341495) was dependent on the medium refreshment conditions, although in reversed order. When using normal culture medium the peak of LY341495 was the largest,  $-1.62 \pm 0.06 \Delta\text{CI}$  (Fig. 1F). Treatment of culture medium with GPT already reduced the peak slightly, but when medium was refreshed by serum-free medium peaks were significantly reduced to minimum levels of  $-0.92 \pm 0.08 \Delta\text{CI}$ . Moreover, addition of GPT did not further increase the minimum peak of LY341495 ( $-0.98 \pm 0.06 \Delta\text{CI}$ , Fig. 1F), indicating a relatively large response of the compound on its own. Interestingly, in serum-free medium with GPT, the trace returned to baseline more readily after the peak (Fig. 1E), indicating that the difference in glutamate levels still slightly altered the shape of the trace. Importantly, no compound-induced responses were observed for both LY354740 and LY341495 at  $1 \mu\text{M}$  in parental wild-type CHO-K1 cells (Fig. 1C,E), confirming that all responses were mGlu<sub>2</sub> receptor-mediated. This was in line with our previous observation that PAM JNJ-46281222 did not induce significant responses on parental CHO-K1 cells as shown in **chapter 4**.

Taken together, the lowest level of endogenous glutamate was reached by medium refreshment with serum-free medium supplemented with GPT, which was used for all further experiments. Of note, the presence of the glutamate degrading enzyme GPT excluded further experimentation with exogenous glutamate, since such experiments would not result in meaningful parameters for potency and/or efficacy. The responses of LY354740 and LY341495 were affected by the different endogenous glutamate concentrations from the culture medium. LY354740 peaks increased upon reduction of endogenous glutamate levels. On the contrary, LY341495 peaks were reduced when endogenous glutamate levels were lowered. Both observations indicate competition of the two molecules for the orthosteric glutamate binding site, which has been shown in radioligand binding experiments with [<sup>3</sup>H]LY354740 and [<sup>3</sup>H]LY341495 as the radioligands.<sup>40,41</sup>

### Agonist LY354740 and antagonist LY341495 induced concentration-dependent responses at low levels of endogenous glutamate

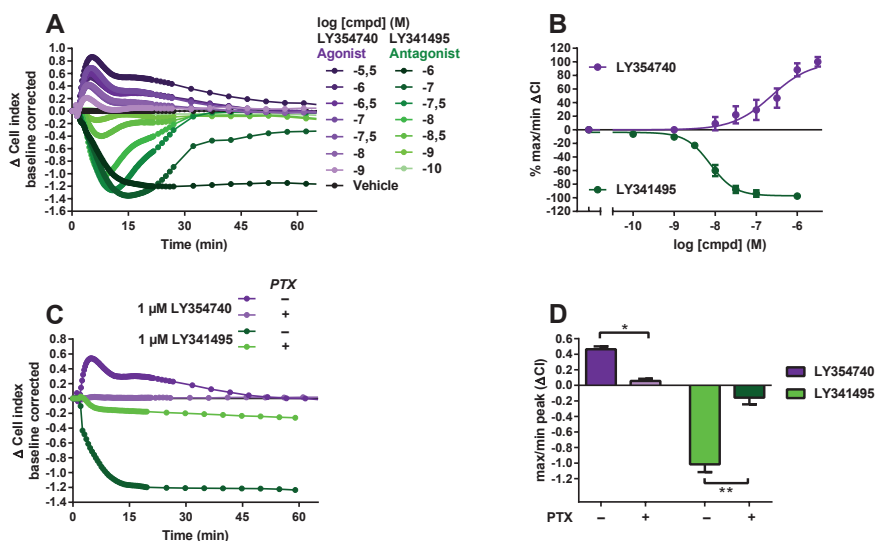
Once the assay conditions were optimized, the potency of agonist LY354740 and antagonist LY341495 were determined. For LY354740 the impedance increased concentration-dependently with a “positive” peak (i.e. positive  $\Delta CI$  values) around 10 minutes, then gradually decreasing with a second ‘shoulder’ peak around 20 minutes (Fig. 2A). A concentration-response curve obtained from the maximum peak levels within the first 60 minutes after stimulation revealed a  $pEC_{50}$  value of  $6.70 \pm 0.24$  (Table 2; Fig. 2B). This potency was lower than observed in other assay types such as  $Ca^{2+}$  mobilization ( $pEC_{50}$  7.4)<sup>42</sup> and similar to the potency obtained in electrophysiology experiments on hippocampal slices ( $pEC_{50}$  6.9).<sup>43</sup>

**Table 2** Potency ( $pEC_{50}$  or  $pIC_{50}$ ) of ligands at the  $mGlu_2$  receptor in CHO-K1\_hmGlu<sub>2</sub> cells after refreshment of medium by serum-free medium containing GPT (3 U/ml) and pyruvate (3 mM).

Compound		$pEC_{50}$	$pIC_{50}$
LY354740	<i>Agonist</i>	$6.70 \pm 0.24$	-
LY341495	<i>Antagonist</i>	-	$8.15 \pm 0.09$
JNJ-46281222	<i>PAM</i>	$7.17 \pm 0.24$	-
RO4491533	<i>NAM</i>	-	$7.34 \pm 0.19$

$pEC_{50}/IC_{50}$  data are shown as mean  $\pm$  SEM from at least three individual experiments performed in duplicate.

Stimulation with increasing concentrations of the antagonist LY341495 resulted in concentration-dependent negative peaks with a minimum around 15 minutes (Fig. 2A). For low concentrations it took around 30 minutes to return to baseline, while at 0.1 and 1  $\mu M$  LY341495 the trace returned to baseline after 120 or 180 minutes, respectively (data not shown). A  $pIC_{50}$  value of  $8.15 \pm 0.09$  was obtained from the minimum peak levels (Fig. 2B; Table 2), which was in agreement with potencies reported before using cAMP,  $Ca^{2+}$ -mobilization and [<sup>35</sup>S]GTP $\gamma$ S assays.<sup>14,31</sup> The concentration-response curve of LY354740 had a pseudo-Hill coefficient of around unity ( $n_H$  0.92) compared to the curve of LY341495 that was much steeper ( $n_H$  -1.81). As mentioned before, LY341495 showed negative responses in Cell Index, indicating that it exhibits an opposite pharmacological effect compared to the agonist LY354740, resulting in an opposite impedance measured. Similar observations have been seen using other label-free systems (i.e. the CellKey and EPIC system), in which agonists induced an increase in response, while inverse agonists caused a decrease in response.<sup>144</sup> However, these studies do not present a mechanistic understanding as they were performed on two non-disclosed GPCRs. Given that in these studies inverse agonists induced negative responses, LY341495 may also be an inverse agonist at the  $mGlu_2$  receptor, especially since the concentration of endogenous glutamate was reduced to a level only slightly able to activate the receptor.



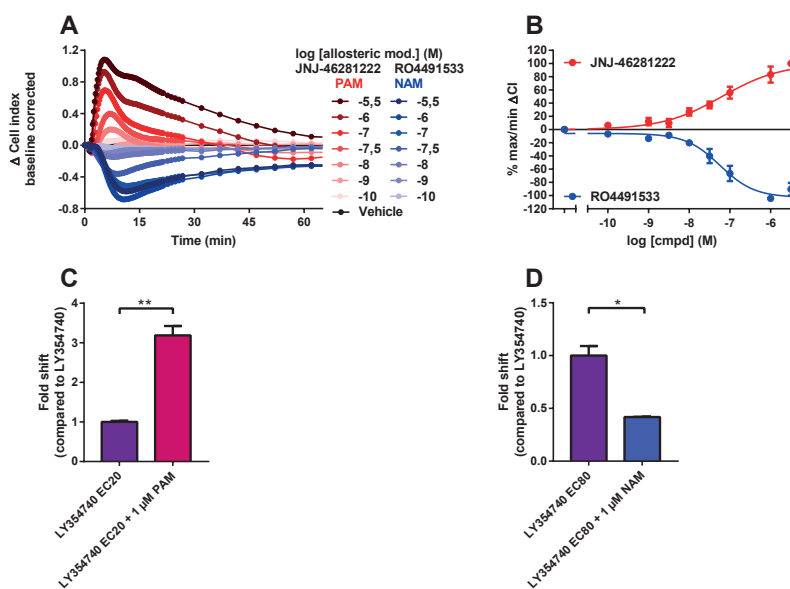
**Figure 2.** Agonist LY354740 and antagonist LY341495-induced concentration-effect responses at low concentration of endogenous glutamate ( $1.6 \pm 0.09 \mu\text{M}$ ). A) Cells were stimulated by increasing concentrations of agonist LY354740 or antagonist LY341495. B) Concentration-response curves were obtained from maximum (LY354740) or minimum (LY341495)  $\Delta\text{CI}$  values and normalized from vehicle-induced  $\Delta\text{CI}$  (0%) to maximum or minimum  $\Delta\text{CI}$  (100% or -100% respectively). C) Responses of  $1 \mu\text{M}$  LY354740 and  $1 \mu\text{M}$  LY341495 in the absence or presence of PTX (300 ng/ml). D) Comparison of maximum peak values induced by  $1 \mu\text{M}$  LY354740 and minimum peak values induced by  $1 \mu\text{M}$  LY341495 in the absence or presence of PTX (300 ng/ml). All xCELLigence traces are from representative experiments performed in duplicate. Concentration-response curves (panel B) represent mean  $\pm$  SEM of at least three individual experiments performed in duplicate. Bar graphs represent mean  $\pm$  SEM of at least three individual experiments performed in duplicate. Statistical analysis was performed using a two-tailed unpaired Student's t-test. \*  $p < 0.01$ , \*\*  $p < 0.001$ .

Finally, the selective  $G\alpha_{i/o}$  inhibitor PTX was used to evaluate whether the effects induced by the agonist LY354740 and antagonist LY341495 were mediated via  $G\alpha_{i/o}$  protein-dependent signaling. Responses of LY354740 and LY341495 were almost completely lost in the presence of PTX, which indicated that the opposite compound-induced cellular responses were both resulting from signaling via  $G\alpha_{i/o}$  (Fig. 2C,D). The residual responses in the presence of PTX most likely represent incomplete inhibition of the  $G\alpha_{i/o}$ -mediated signaling.

### Agonist efficacy was increased by PAM and decreased by NAM treatment

Before measuring the effect of allosteric modulators on agonist efficacy, responses of a PAM and a NAM in the absence of exogenous agonist were determined. Both allosteric modulators showed responses on their own without added agonist, which were likely caused by the low level of endogenous glutamate ( $1.6 \pm 0.09 \mu\text{M}$ ) still present in the serum-free culture medium with GPT (Table 1). Stimulation with the PAM JNJ-46281222 resulted in positive dose-dependent responses, leading to a  $p\text{EC}_{50}$  of  $7.17 \pm 0.24$  for this compound (Table 2; Fig. 3A,B).

The potency of the PAM was lower than in a [ $^{35}$ S]GTP $\gamma$ S assay as shown in **chapter 2** ( $pEC_{50}$  of 7.71).<sup>23</sup> This may be caused by the concentration of endogenous glutamate that is lower than the typical  $EC_{20}$  glutamate concentrations used in standard [ $^{35}$ S]GTP $\gamma$ S assays used to determine the potency of allosteric modulators or by the differences in assay types.<sup>45,46</sup> Treatment with the NAM RO4491533 induced negative peaks in Cell Index yielding a  $pIC_{50}$  value of  $7.34 \pm 0.19$ , which was lower than observed before in a [ $^{35}$ S]GTP $\gamma$ S assay ( $pIC_{50}$  8.7).<sup>45</sup> In this case the difference may be due to the high  $EC_{80}$  glutamate concentration used in the [ $^{35}$ S]GTP $\gamma$ S assay or, again, due to the differences in assay type. The concentration-response curve of JNJ-46281222 was shallow with a pseudo-Hill coefficient of 0.59 compared to RO4491533's which was around unity ( $n_H$  -1.02). Of note, this is the first observation that Cell Indices go up in the presence of a PAM and down when using a NAM, like JNJ-46281222 and RO4491533, respectively. In that sense, the effects of allosteric modulators for the mGlu $_2$  receptor resemble orthosteric compound-induced responses as described above.



**Figure 3.** Positive allosteric modulator (PAM) JNJ-46281222 and negative allosteric modulator (NAM) RO4491533-induced responses at low concentration ( $1.6 \pm 0.09 \mu\text{M}$ ) of endogenous glutamate. A) Cells were stimulated by increasing concentrations of JNJ-46281222 or RO4491533. B) Concentration-response curves were obtained from maximum (JNJ-46281222) or minimum (RO4491533)  $\Delta\text{CI}$  values and normalized from vehicle-induced  $\Delta\text{CI}$  values (0%) to maximum (100%) or minimum (-100%)  $\Delta\text{CI}$  values. C) Responses induced by an  $EC_{20}$  LY354740 concentration in the absence and presence of  $1 \mu\text{M}$  JNJ-46281222. D) Responses induced by an  $EC_{80}$  LY354740 concentration in the absence and presence of  $1 \mu\text{M}$  RO4491533. xCELLigence traces are from representative experiments performed in duplicate. Bar graphs represent mean  $\pm$  SEM of at least three experiments performed in duplicate, where data was normalized to the response of PAM or NAM on itself (1.0). Statistical analysis was performed using a two-tailed unpaired Student's t-test. \*  $p < 0.01$ , \*\*  $p < 0.001$ .

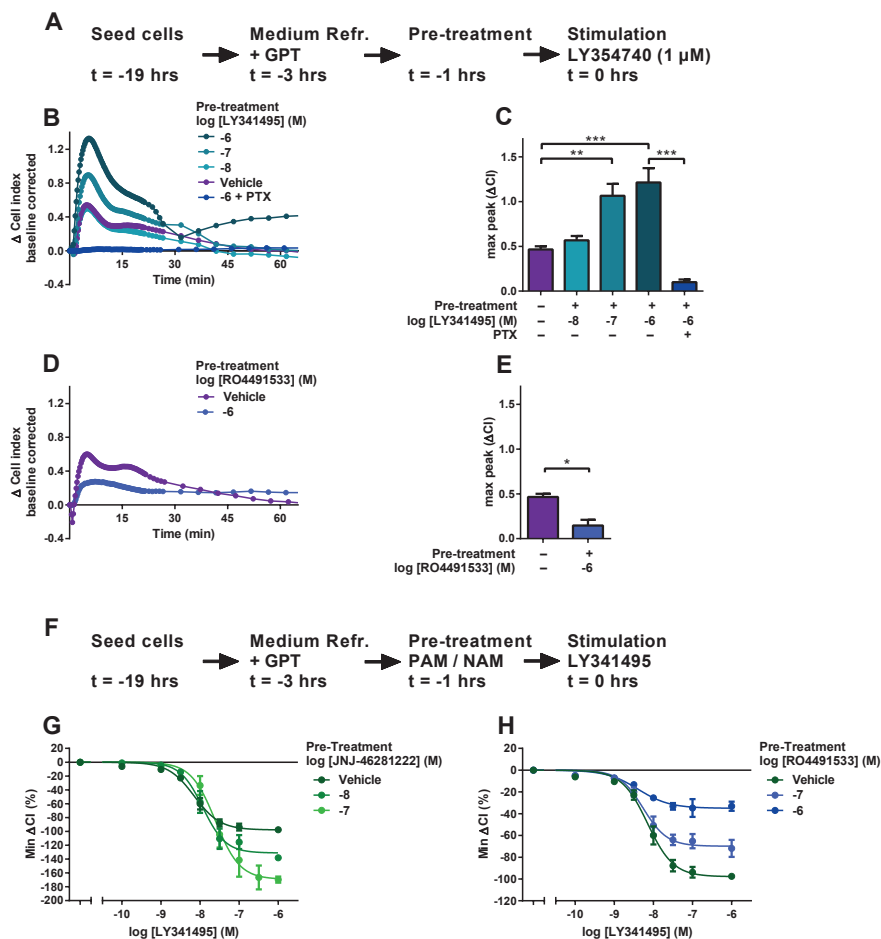


To study the effects of a PAM on agonist efficacy, cellular responses to an LY354740 concentration equivalent to its EC<sub>20</sub> response (30 nM) were determined in the absence and presence of 1 μM JNJ-46281222. This resulted in a significant 3-fold increase in the LY354740 peak response, confirming that JNJ-46281222 behaves as a PAM for this agonist (Fig. 3C). The effect of 1 μM of the NAM RO4491533 was determined using an LY354740 concentration equivalent to its EC<sub>80</sub> concentration (300 nM). This yielded a significant, more than twofold reduction in the response of LY354740 (Fig. 3D), which is a typical NAM effect. These experiments showed that xCELLigence is able to assess the effects of allosteric modulators on agonist efficacy, which is in line with work reported by Chen *et al.* (2015)<sup>47</sup> on allosteric modulation of the M<sub>4</sub> muscarinic acetylcholine receptor.

### LY341495 pre-treatment revealed constitutive receptor activity

The maximum peak height of the agonist LY354740 was much lower compared to the negative peaks of the antagonist LY341495 (Fig. 2 A,C). In order to study the underlying mechanism, cells were pretreated with 1 μM LY341495 1 hour prior to stimulation (Fig. 4A). The response of subsequent stimulation by 1 μM LY354740 was increased significantly from an average max peak of  $0.47 \pm 0.04 \Delta\text{CI}$  up to a level of  $1.21 \pm 0.16$  (Fig. 4B,C). This was opposite to the expected loss of agonist response by the pre-treatment with a high concentration of a competitive antagonist that is still present at the time of stimulation with agonist. The effect of LY341495 pre-treatment on the LY354740 peak was concentration-dependent: pre-treatment with 10 nM LY341495 slightly increased LY354740 traces, whereas 100 nM and 1 μM LY341495 were able to further and significantly increase the peak height of 1 μM LY354740 stimulation (Fig. 4C). All traces reached baseline after 30-45 minutes. In contrast to the other traces, the trace of 1 μM LY354740 after pre-treatment with 1 μM LY341495 increased slightly after that point reaching a plateau around  $0.4 \Delta\text{CI}$ . Treatment with the selective Gα<sub>i/o</sub> inhibitor PTX revealed that the LY354740 response after pre-treatment with LY341495 was lost in the presence of PTX, indicating that this is also a mostly, if not fully, Gα<sub>i/o</sub>-mediated response (Fig. 4B,C). In contrast to LY341495, pre-treatment with 1 μM of the NAM RO4491533 resulted in a typical reduced agonist response of LY354740 (Fig. 4D,E).

Together, these results show that LY341495 increased the window of agonist response by almost 3-fold. This is a larger increase than can be explained by the level of endogenous glutamate (1.6 μM at stimulation), which might enable approximately 10% receptor activation. Blockade of glutamate binding may thus increase the agonist-induced response by a similar level. Therefore, we believe that the increased agonist response after pre-treatment with LY341495 indicates that the receptor is constitutively active and that LY341495 is behaving as an inverse agonist. This was confirmed by the fact that, in contrast to pre-treatment with LY341495, pre-treatment by the NAM RO4491533 resulted in a decreased agonist response (Fig. 4D,E). Such a decreased agonist response is similar to the expected effect of pre-treatment with a neutral antagonist.



**Figure 4.** Evaluation of LY341495 inverse agonism. A) Set-up of experiments. B) Cells were stimulated with  $1 \mu\text{M}$  LY354740 after pre-treatment with increasing concentrations of LY341495. Pre-treatment with  $1 \mu\text{M}$  LY341495 was also performed in the presence of PTX ( $300 \text{ ng/ml}$ ). C) Comparison of maximum peak values induced by  $1 \mu\text{M}$  LY354740 after pre-treatment with increasing concentrations of LY341495. Pre-treatment with  $1 \mu\text{M}$  LY341495 was also performed in the presence of PTX ( $300 \text{ ng/ml}$ ). D) Cells were stimulated with  $1 \mu\text{M}$  LY354740 after pre-treatment with  $1 \mu\text{M}$  NAM RO4491533 or vehicle. E) Comparison of maximum peak values induced by  $1 \mu\text{M}$  LY354740 after pre-treatment with  $1 \mu\text{M}$  RO4491533 or vehicle. F) Set-up of experiments. G,H) Concentration-response curves were obtained from minimum  $\Delta\text{CI}$  values and normalized from vehicle-induced  $\Delta\text{CI}$  values (0%) to minimum (-100%)  $\Delta\text{CI}$  values after vehicle pre-treatment. xCELLigence traces are from representative experiments performed in duplicate. Bar graphs represent mean  $\pm$  SEM of at least three individual experiments performed in duplicate. Concentration-response curves represent mean  $\pm$  SEM of at least three individual experiments performed in duplicate. Statistical analysis was performed using a one-way ANOVA with Dunnett's (C) post-test or using a two-tailed unpaired Student's t-test (E). \* p < 0.01, \*\* p < 0.001, \*\*\* p < 0.0001.

To further assess the inverse agonism of LY341495, concentration-response curves were obtained after pre-treatment with increasing concentrations of the PAM JNJ-46281222 (Fig. 4F,G). The curves shifted from a pIC<sub>50</sub> of 8.15 ± 0.09 without PAM pre-treatment to 7.89 ± 0.13 in the presence of 10 nM PAM, to 7.55 ± 0.13 in the presence of 100 nM PAM. Such a modulatory shift in potency in the presence of a PAM is typical for an inverse agonist and is not expected for a neutral antagonist.<sup>48,49</sup> Next to the shift in potency, increasing concentrations of PAM pre-treatment resulted in a larger window of LY341495 response. On the contrary, pre-treatment with NAM RO4491533 did not result in significant alteration in LY341495 potency (Fig. 4H), a pIC<sub>50</sub> values of 8.22 ± 0.14 in the presence of 100 nM NAM and 8.35 ± 0.12 in the presence of 1 μM NAM were found. The efficacy window of LY341495 was reduced dose-dependently up to more than 60% at 1 μM NAM, showing that the NAM is not only able to strongly reduce agonist efficacy without changing potency,<sup>31</sup> but similarly affects the inverse agonist activity of LY341495.

A shift in LY341495 potency induced by the PAM could be the reason of increased potency of endogenous glutamate. However, the large shift in efficacy cannot be explained by presence of endogenous agonist, nor can the large reduction of efficacy after NAM pre-treatment. Together, inverse agonism by LY341495 was further confirmed by these PAM and NAM pre-treatment experiments in this system that measures phenotypic morphological responses of the whole cell, in this case via the Gα<sub>i/o</sub> signaling pathway. On a separate note, receptor desensitization induced by endogenous glutamate could be of concern here. However, the mGlu<sub>2</sub> receptor is known to be resistant to agonist-induced desensitization which was also seen in our hands in repeated stimulation experiments (data not shown).<sup>50,51</sup> Doumazane *et al.* (2013)<sup>52</sup> found a higher FRET signal after application of 1 μM LY341495, similar to the effect of LY341495 pre-treatment presented here. These authors reasoned that this effect was mediated by either constitutive activity or presence of endogenous glutamate, which was not elucidated any further. Inverse agonism by LY341495 has been reported before. For example, DiRaddo *et al.* (2014)<sup>53</sup> found that LY341495 was behaving as inverse agonist after pre-treatment with agonist, when using the Glo-sensor cAMP assay with CHO-K1 cells stably expressing the mGlu<sub>2</sub> receptor. Moreover, inverse agonism by LY341495 at the mGlu<sub>2</sub> receptor was also seen in studies investigating receptor cross-signaling in mGlu<sub>2</sub>-5HT<sub>2A</sub> heterocomplexes.<sup>54,55</sup> Generally, LY341495 is considered a neutral antagonist for the mGlu<sub>2</sub> receptor<sup>14,15</sup> as most *in vitro* assays did not yield inverse agonism, which is likely due to differences in cell lines or assay systems used.

## CONCLUSION

In conclusion, we have validated the use of the impedance-based biosensor xCELLigence system to study mGlu<sub>2</sub> pharmacology. High levels of endogenous glutamate reduced the agonist activation window and therefore efforts were made to reduce these. We characterized mGlu<sub>2</sub> signaling with an agonist, antagonist and both positive and negative allosteric modulators; the latter two modulated the response of both orthosteric agonist and antagonist. Remarkable and opposite effects on impedance were observed for compounds with opposite pharmacological effects. Both the agonist and PAM increased impedance whereas the antagonist and NAM decreased this read-out. Importantly, we show that constitutive mGlu<sub>2</sub> receptor activity could be inhibited by the antagonist LY341495 which therefore behaved as an inverse agonist in the system used. The present study provides an extended ensemble of the properties of mGlu<sub>2</sub> ligands in comparison to conventional *in vitro* assays. Together the results show that label-free biosensors, such as the xCELLigence, are valuable tools in drug discovery and pharmacological profiling at the mGlu<sub>2</sub> receptor as well as other GPCRs

## REFERENCES

1. Scott CW, Peters MF. *Drug Discov Today*. **2010**; 15: 704–716.
2. Fang Y. *Expert Opin Drug Discov*. **2015**; 10: 331–343.
3. Yu N, Atienza JM, Bernard J, Blanc S, Zhu J, Wang X, Xu X, Abassi Y. *Anal Chem*. **2006**; 78: 35–43.
4. Halai R, Cooper M a. *Expert Opin Drug Discov*. **2012**; 7: 123–31.
5. Hillger JM, Lieuw W-L, Heitman LH, IJzerman AP. *Drug Discov Today*. **2017**; 0.
6. Lundstrom K. *Expert Opin Drug Discov*. **2017**; 12: 335–343.
7. Hillger JM, Schoop J, Boomsma DI, Eline Slagboom P, IJzerman AP, Heitman LH. *Biosens Bioelectron*. **2015**; 74: 233–242.
8. Nederpelt I, Vergroesen RD, IJzerman AP, Heitman LH. *Biosens Bioelectron*. **2016**; 79: 721–727.
9. Grundmann M, Tikhonova IG, Hudson BD, Milligan G, Kenakin T, Grundmann M, Tikhonova IG, Hudson BD, Smith NJ, Mohr K, Ulven T. *Cell Chem Biol*. **2016**; 23: 392–403.
10. Marek GJ. *Eur J Pharmacol*. **2010**; 639: 81–90.
11. Niswender CM, Conn PJ. *Annu Rev Pharmacol Toxicol*. **2010**; 50: 295–322.
12. Patil ST, Zhang L, Martenyi F, Lowe SL, Jackson KA, Andreev B V, Avedisova AS, Bardenstein LM, Gurovich IY, Morozova MA, Mosolov SN, Neznanov NG, Reznik AM, Smulevich AB, Tochilov VA, Johnson BG, Monn JA, Schoepp DD. *Nat Med*. **2007**; 13: 1102–7.

13. Adams DH, Kinon BJ, Baygani S, Millen BA, Velona I, Kollack-Walker S, Walling DP. *BMC Psychiatry*. **2013**; 13: 143.
14. Kingston A., Ornstein P., Wright R., Johnson B., Mayne N., Burnett J., Belagaje R, Wu S, Schoepp D. *Neuropharmacology*. **1998**; 37: 1–12.
15. Witkin JM, Mitchell S, Wafford K, Carter G, Gilmour G, Li J, Eastwood B, Overshiner C, Li X, Rorick-Kehn L, Rasmussen K, Anderson W, Nikolayev A, Tolstikov V, Kuo M-S, Catlow J, Li R, Smith S, Mitch C, Ornstein P, Swanson S, Monn J. *J Pharmacol Exp Ther*. **2017**; jpet.116.238121.
16. Conn PJ, Lindsley CW, Meiler J, Niswender CM. *Nat Rev Drug Discov*. **2014**; 13: 692–708.
17. Wu H, Wang C, Gregory KJ, Han GW, Cho HP, Xia Y, Niswender CM, Katritch V, Meiler J, Cherezov V, Conn PJ, Stevens RC. *Science*. **2014**; 344: 58–64.
18. Doré AS, Okrasa K, Patel JC, Serrano-Vega M, Bennett K, Cooke RM, Errey JC, Jazayeri A, Khan S, Tehan B, Weir M, Wiggin GR, Marshall FH. *Nature*. **2014**; 511: 557–62.
19. Gregory KJ, Dong EN, Meiler J, Conn PJ. *Neuropharmacology*. **2011**; 60: 66–81.
20. Christopoulos A, Changeux J-P, Catterall WA, Fabbro D, Burris TP, Cidlowski JA, Olsen RW, Peters JA, Neubig RR, Pin J-P, Sexton PM, Kenakin TP, Ehlert FJ, Spedding M, Langmead CJ. *Pharmacol Rev*. **2014**; 66: 918–947.
21. Lavreysen H, Langlois X, Ahnaou A, Drinkenburg W, te Riele P, Biesmans I, Van der Linden I, Peeters L, Megens A, Wintmolders C, Cid JM, Trabanco AA, Andrés JL, Dautzenberg FM, Lütjens R, Macdonald G, Atack JR. *J Pharmacol Exp Ther*. **2013**; 346: 514–27.
22. Galici R, Echemendia NG, Rodriguez AL, Conn PJ. *J Pharmacol Exp Ther*. **2005**; 315: 1181–7.
23. Doornbos MLJ, Pérez-Benito L, Tresadern G, Mulder-Krieger T, Biesmans I, Trabanco AA, Cid JM, Lavreysen H, IJzerman AP, Heitman LH. *Br J Pharmacol*. **2016**; 173: 588–600.
24. Cid JM, Tresadern G, Duvey G, Lütjens R, Finn T, Rocher J, Poli S, Vega JA, de Lucas AI, Matesanz E, Linares ML, Andrés JL, Alcazar J, Alonso JM, Macdonald GJ, Oehlich D, Lavreysen H, Ahnaou A, Drinkenburg W, Mackie C, Pype S, Gallacher D, Trabanco AA. *J Med Chem*. **2014**; 57: 6495–512.
25. Lavreysen H, Ahnaou A, Drinkenburg W, Langlois X, Mackie C, Pype S, Lütjens R, Le Poul E, Trabanco AA, Nuñez JMC. *Pharmacol Res Perspect*. **2015**; 3: e00096.
26. Lavreysen H, Langlois X, Ver Donck L, Cid Nuñez JM, Pype S, Lütjens R, Megens A. *Pharmacol Res Perspect*. **2015**; 3: e00097.
27. Salih H, Anghelescu I, Kezic I, Sinha V, Hoeben E, Van Nueten L, De Smedt H, De Boer P. *J Psychopharmacol*. **2015**; 29: 414–425.
28. Kent JM, Daly E, Kezic I, Lane R, Lim P, De Smedt H, De Boer P, Van Nueten L, Drevets WC, Ceusters M. *Prog Neuro-Psychopharmacology Biol Psychiatry*. **2016**; 67: 66–73.
29. Cook D, Brown D, Alexander R, March R, Morgan P, Satterthwaite G, Pangalos MN. *Nat Rev Drug Discov*. **2014**; 13: 419–31.
30. Goeldner C, Ballard TM, Knoflach F, Wichmann J, Gatti S, Umbricht D. *Neuropharmacology*. **2013**; 64: 337–46.
31. Campo B, Kalinichev M, Lambeng N, El Yacoubi M, Royer-Urios I, Schneider M, Legrand C, Parron D, Girard F, Bessif A, Poli S, Vaugeois J-M, Le Poul E, Celanire S. *J Neurogenet*. **2011**; 25: 152–66.
32. Van Gool M, Alonso De Diego SA, Delgado O, Trabanco AA, Jourdan F, Macdonald GJ, Somers M, Ver Donck L. *ChemMedChem*. **2017**; 12: 905–912.
33. Xi B, Yu N, Wang X, Xu X, Abassi YA. *Biotechnol J*. **2008**; 3: 484–495.
34. Wahrheit J, Nicolae A, Heinzele E. *BMC Proc*. **2013**; 7: P44.
35. Pin JP, De Colle C, Bessis AS, Acher F. *Eur J Pharmacol*. **1999**; 375: 277–94.
36. Lavreysen H, Le Poul E, Van Gompel P, Dillen L, Leysen JE, Lesage ASJ. *Mol Pharmacol*. **2002**; 61: 1244–54.

37. Sengmany K, Singh J, Stewart GD, Conn PJ, Christopoulos A, Gregory KJ. *Neuropharmacology*. **2017**; 115: 60–72.
38. Scandroglio P, Brusa R, Lozza G, Mancini I, Petrò R, Reggiani A, Beltramo M. *J Biomol Screen*. **2010**; 15: 1238–47.
39. Lieb S, Michaelis S, Plank N, Bernhardt G, Buschauer A, Wegener J. *Pharmacol Res*. **2016**; 108: 65–74.
40. Johnson BG, Wright R a, Arnold MB, Wheeler WJ, Ornstein PL, Schoepp DD. *Neuropharmacology*. **1999**; 38: 1519–29.
41. Schaffhauser H, Richards JG, Cartmell J, Chaboz S, Kemp JA, Klingelschmidt A, Messer J, Stadler H, Woltering T, Mutel V. *Mol Pharmacol*. **1998**; 53: 228–33.
42. Monn JA, Prieto L, Taboada L, Pedregal C, Hao J, Reinhard MR, Henry SS, Goldsmith PJ, Beadle CD, Walton L, Man T, Rudyk H, Clark B, Tupper D, Baker SR, Lamas C, Montero C, Marcos A, Blanco J, Bures M, Clawson DK, Atwell S, Lu F, Wang J, Russell M, Heinz BA, Wang X, Carter JH, Xiang C, Catlow JT, Swanson S, Sanger H, Broad LM, Johnson MP, Knopp KL, Simmons RM a, Johnson BG, Shaw DB, McKinzie DL. *J Med Chem*. **2015**; 58: 1776–1794.
43. Kilbride J, Huang L, Rowan MJ, Anwyl R. *Eur J Pharmacol*. **1998**; 356: 149–157.
44. Lee PH, Gao A, van Staden C, Ly J, Salon J, Xu A, Fang Y, Verkleeren R. *Assay Drug Dev Technol*. **2008**; 6: 83–94.
45. Pérez-Benito L, Doornbos MLJ, Cordini A, Peeters L, Lavreysen H, Pardo L, Tresadern G. *Structure*. **2017**; 25: 1–10.
46. Kenakin TP. *A Pharmacology Primer - fourth edition*, Academic Press: San Diego, **2014**.
47. Chen ANY, Malone DT, Pabreja K, Sexton PM, Christopoulos A, Canals M. *J Biomol Screen*. **2015**; 20: 646–654.
48. Lane JR, May LT, Parton RG, Sexton PM, Christopoulos A. *Nat Chem Biol*. **2017**; 13: 929–937.
49. Canals M, Lane JR, Wen A, Scammells PJ, Sexton PM, Christopoulos A. *J Biol Chem*. **2012**; 287: 650–659.
50. Iacovelli L, Molinaro G, Battaglia G, Motolese M, Di Menna L, Alfiero M, Blahos J, Matrisciano F, Corsi M, Corti C, Bruno V, De Blasi A, Nicoletti F. *Mol Pharmacol*. **2009**; 75: 991–1003.
51. Lennon SM, Rivero G, Matharu A, Howson P a, Jane DE, Roberts PJ, Kelly E. *Eur J Pharmacol*. **2010**; 649: 29–37.
52. Doumazane E, Scholler P, Fabre L, Zwier JM, Trinquet E, Pin J-P, Rondard P. *Proc Natl Acad Sci U S A*. **2013**; 110: E1416–25.
53. DiRaddo JO, Miller EJ, Hathaway H a, Grajkowska E, Wroblewska B, Wolfe BB, Liotta DC, Wroblewski JT. *J Pharmacol Exp Ther*. **2014**; 349: 373–82.
54. Fribourg M, Moreno JL, Holloway T, Provasi D, Baki L, Mahajan R, Park G, Adney SK, Hatcher C, Eltit JM, Ruta JD, Albizu L, Li Z, Umali A, Shim J, Fabiato A, MacKerell AD, Brezina V, Sealfon SC, Filizola M, González-Maeso J, Logothetis DE. *Cell*. **2011**; 147: 1011–23.
55. Baki L, Fribourg M, Younkin J, Eltit JM, Moreno JL, Park G, Vysotskaya Z, Narahari A, Sealfon SC, Gonzalez-Maeso J, Logothetis DE. *Pflügers Arch - Eur J Physiol*. **2016**; 468: 775–793.