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Characterization of L-Theanine excitatory actions on hippocampal neurons: towards the generation of novel N-methyl-D-aspartate receptor modulators based on its backbone

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Key words: L-Theanine, L- γ -N-propyl-glutamine, Microwave-assisted organic synthesis (MAOS), NMDA receptors, intracellular Ca²⁺ homeostasis, hippocampal neurons, Xenopus oocytes, expression, GluN2A, GluN2B

Abstract

L-Theanine (or L- γ -N-ethyl-glutamine) is the major amino acid found in *Camellia sinensis*. It has received much attention because of its pleiotropic physiological and pharmacological activities leading to health benefits in humans, especially. We describe here a new, easy, efficient and environmentally-friendly chemical synthesis of L-Theanine and L- γ -N-propyl-Gln and their corresponding D isomers. L-Theanine, and its derivatives obtained so far, exhibited partial co-agonistic action at N-methyl-D-aspartate (NMDA) receptors, with no detectable agonist effect at other glutamate receptors, on cultured hippocampal neurons. This activity was retained on NMDA receptors expressed in *Xenopus* oocytes. In addition, both GluN2A and GluN2B containing NMDA receptors were equally modulated by L-Theanine. The stereochemical change from L-Theanine to D-Theanine along to the substitution of the ethyl for a propyl moiety in the γ -N position of L- and D-Theanine significantly enhanced the biological efficacy, as measured on cultured hippocampal neurons. L-Theanine structure thus represents an interesting backbone to develop novel NMDA receptor modulators.

Introduction

L-Theanine (L- γ -N-ethyl-glutamine) is the major amino acid found in green tea (*Camellia sinensis*). It represents, on average, 2% of the weight of dried green tea leaves. The multiple health benefits of this amino acid are widely studied. This is particularly relevant in the central nervous system, as L-Theanine easily crosses the blood-brain barrier¹. In humans, L-Theanine has been shown to induce anti-stress/relaxing actions^{2,3} and to improve sleep induction⁴. Further characterizations of its actions on animal models of Alzheimer's disease⁵ and stroke⁶ indicate that L-Theanine also displays neuroprotective action^{7,8} which seems to rely on an antioxidant action⁵ and/or on modulation of neurotransmission, especially the excitatory and inhibitory ones. Indeed, L-Theanine shares a lot of structural similarities with glutamate and ligand-binding studies have established affinities for ionotropic, *i.e.* kainate, α -amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) and N-methyl-D-aspartic acid (NMDA) receptors⁹. Its neuroprotective actions may rely on interference with ionotropic or metabotropic glutamate receptor-mediated neuronal processes^{10,11}. The prevention of ischemic damage in the gerbil hippocampus could be attributed to the blockade of AMPA receptors which actively contribute to ischemic injury^{7,12}. In addition, L-Theanine may also modulate GABAergic transmission to produce neuroprotection under ischemia as evidenced in mice⁶. Other studies uncovered an excitatory action of L-Theanine. Indeed, in striatal neurons, L-Theanine treatment increases the exocytosis of various neurotransmitters, including γ -amino-butyric acid (GABA), glycine and dopamine¹³. This could be due to a pleiotropic action on glutamatergic receptors. In this line, it has been shown that the excitatory action of L-Theanine on cortical neurons can be blocked by NMDA receptor antagonists¹⁴. This could explain the beneficial action of L-Theanine on a rodent model of schizophrenia induced by NMDA receptors hypo function. Indeed, NMDA receptors are widely expressed on inhibitory interneurons. Their activation stimulates GABA release and thus regulates the excitability of excitatory cells. This is particularly relevant in the prefrontal cortex where a subset of GABAergic interneurons activated by cortical neurons regulate the excitability of thalamic neurons, themselves exciting cortical neurons (so called 'thalamo-cortical loop'). Preventing the activity of these interneurons, by blocking NMDA receptors, for instance, leads to dysregulation of the thalamo-cortical loop and to the occurrence of pathological conditions as psychosis¹⁵. Interestingly, L-Theanine treatment reverses sensorimotor gating deficits which are associated with this pathological state¹⁴. In addition, partial agonists of the glycine site on NMDA receptors, as D-cycloserine, have proved to

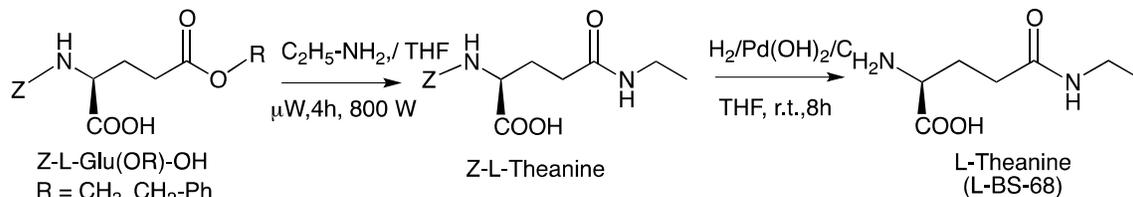
1 exhibited beneficial effects to alleviate the symptoms of various psychiatric diseases ¹⁶.
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3 Therefore, targeting the glycine binding site with partial agonists represents an interesting
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5 route to normalize NMDA receptor activity.

6 NMDA receptors have long been associated with the synaptic plasticity that produces the
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8 long-term potentiation ¹⁷ and the long-term depression ¹⁸ in the hippocampus. However, the
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10 molecular mechanisms responsible for the differential role of NMDA receptors of distinct
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12 subunit composition are still poorly understood. L-Theanine could thus be an interesting
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14 backbone for the synthesis of new modulators of the NMDA receptor with applications in
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16 both fundamental research and therapeutic usage for NMDA receptors-associated pathologies
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18 (schizophrenia ¹⁹ and neurodevelopmental disorders ²⁰). We provide here a new, simple and
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20 efficient synthesis of D and L-Theanine and N-alkylated derivatives. The effects of these
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22 compounds are evaluated on cultured hippocampal neurons and on *Xenopus* oocytes
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24 expressing NMDA receptors.
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Results

Synthesis of theanine and alkylated derivatives

The starting (commercially available) products were N-protected γ -glutamyl esters: Z-L-Glu(O-CH₂-Ph)-OH or Z-L-Glu(OCH₃)-OH and 2M ethylamine solution (Z: benzyloxycarbonyl group). Synthetic L-Theanine was obtained by a new protocol for specific amidification as described in Scheme 1.



Scheme 1: Chemical route to L-Theanine (L-BS-68) synthesis

The reaction has been performed using microwave oven (Biotage initiator 60 EXP) in 2M ethylamine solution in THF (6 equiv). The vessel was heated at different temperatures (for example for 60°C: power: 600W). The reactions were followed by high-performance liquid chromatography (HPLC). Absolutely no hydrolysis of newly synthesized Z-Theanine in Z-Glu-OH was observed and this procedure provided approximately 20-fold acceleration (4 hours *versus* 1 day using conventional methods which led to about 40% of hydrolysis of Z-Theanine in Z-glutamic acid, data not shown).

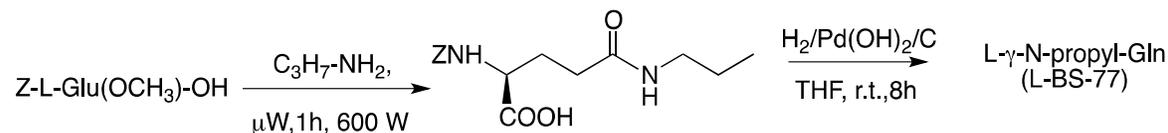
The enantiomeric purity of synthetic Z-L-Theanine was controlled by measuring α_D and further chiral HPLC analyses. To confirm that no racemization took place, the amidification with 2M ethylamine solution in THF has been carried out with the commercially available Z-D-Glu(OCH₃)-OH. Under these conditions, optically pure Z-D-Theanine was obtained in the same yield. Both syntheses have been followed by chiral HPLC separately and both compounds appeared at different retention times.

In a second and final step, synthetic L-Theanine (L-BS-68) was obtained by removing the benzyloxycarbonyl protecting group Z by catalytic hydrogenation in quantitative yield.

The synthesis of L-Theanine congeners by modifying the γ -N-alkyl group was then performed by substituting the γ -N-ethyl group in L-Theanine for other alkyl moieties, in order to enhance the hydrophobicity of the derivatives. We describe here the synthesis of the L- γ -N-propylglutamine (or L-BS-77).

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With Z-L-Glu(OCH₃)-OH as starting product, in solvent free system, thanks to pure liquid n-propylamine (Bp = 47-51°C), and under microwave irradiations, Z-L-γ-N-propylglutamine was quantitatively obtained in only one hour at 60°C (Scheme 2).



Scheme 2: Chemical route to L-γ-N-propyl-Gln (L-BS-77) synthesis

As L-Theanine is closely related to glutamate and GABA, we have also analyzed the purity of L-Theanine by HPLC. Under the elution conditions used, glutamate, L-Theanine and GABA were well separated as single peaks appearing at 2.99, 5.78 and 8.42 min, respectively. L-Theanine on its own contained neither glutamate nor GABA (Figure 1).

L-Theanine is a co-agonist of NMDA receptors

L-Theanine was previously shown to elicit [Ca²⁺]_i increases when applied in the micromolar range on cultured cortical neurons¹⁴. We have thus checked whether L-Theanine was active in this concentration range (1-100μM) on cultured hippocampal neurons. In the absence of Mg²⁺ ions, L-Theanine elicited [Ca²⁺]_i increases which were consistently detected at 1μM in mature (16 days *in vitro*, DIV) cultured hippocampal neurons (Figure 2A). Under physiological extracellular Mg²⁺ (1mM; Figure 2B) or in the presence of NMDA receptor antagonist dizolcipine (MK-801, 10μM; Figure 2C) or without extracellular Ca²⁺ ions (Figure 6D) perfusion of L-Theanine had no effect on [Ca²⁺]_i. These data demonstrate that L-Theanine produced an influx of Ca²⁺ on mature cultured hippocampal neurons which mainly relied on NMDA receptors. Non-NMDA ionotropic receptors and metabotropic mGlu1/5 receptors did not seem to be activated here by L-Theanine, as its effect was fully blocked by MK-801.

Surprisingly, on immature hippocampal neurons (6-8 DIV), L-Theanine (range: 10μM up to 1mM) had absolutely no effect on [Ca²⁺]_i, while NMDA could elicit responses sensitive to glycine (Figure 3A). Therefore, we hypothesized that L-Theanine might be exerting positive allosteric modulation or co-agonist action on NMDA receptors stimulated by the endogenous glutamate release which occurs only in mature cultures of hippocampal neurons as observed previously²¹. L-Theanine was thus tested in combination with NMDA on immature neurons, where synaptic activation of NMDA receptors did not yet occur, and compared its effects with those elicited by conventional NMDA receptor glycine site agonists, *i.e.* glycine and D-serine.

1 L-Theanine (1 μ M-1mM) effectively potentiated Ca²⁺ influxes elicited by NMDA (10 μ M) in a
2 concentration dependent manner with a maximal effect at a concentration of 100 μ M (Figure
3 3B and E). Theanine was significantly less efficient than glycine or D-serine (Figure 3C, D
4 and E). Nevertheless, the action of L-Theanine was rather selective for NMDA receptors.
5 Indeed, we verified whether L-Theanine had any effect on non-NMDA ionotropic receptors.
6 For this, L-Theanine (1mM) was applied in combination with kainate (40 μ M). We observe
7 that kainate-mediated Ca²⁺ responses were totally insensitive to L-Theanine (Figure 3F).
8 Then, to test whether the presence of endogenous glutamate was a necessary prerequisite to
9 observe *per se* effects of L-Theanine on mature cultured neurons, experiments were
10 performed in the presence of tetrodotoxin (TTX; 500nM) a Na⁺ channel blocker which
11 prevents glutamate release and excitatory transmission in these neurons²¹. TTX completely
12 inhibited the changes in [Ca²⁺]_i produced by L-Theanine (10 μ M), glycine (10 μ M) or D-serine
13 (100 μ M) (Figure 4A) in mature cultured neurons. It is noticeable that NMDA response was
14 also partially inhibited. This could be associated with a decreased co-agonist tone obtained by
15 blocking synaptic transmission. However TTX did not prevent the potentiating effect of L-
16 Theanine, glycine or D-serine on NMDA responses, on mature neurons (Figure 4B). Finally,
17 the NMDA glycine binding site antagonist, 7-chlorokynurenic acid (0.1 μ M), completely
18 blocked L-Theanine-mediated [Ca²⁺]_i increases in a reversible manner (Figure 4C). It is
19 noteworthy that at the concentration tested, 7-chlorokynurenic acid had a very modest
20 inhibitory effect on NMDA-mediated [Ca²⁺]_i rises (less than 4%). Taken together, these
21 results confirm that L-Theanine behaves as a partial NMDA receptor co-agonist acting on the
22 glycine site and therefore strictly requires endogenous release of glutamate to produce *per se*
23 effects.
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41 In cultured hippocampal neurons, our experimental procedure used to measure intracellular
42 calcium allowed us to principally observe GluN2B-containing NMDA receptor responses as
43 ifenprodil (10 μ M), a selective antagonist of GluN2B subunit-containing NMDA receptor,
44 completely blocked the NMDA responses (Figure 2B). The selectivity towards either GluN2A
45 or GluN2B-containing NMDA receptors was further evaluated on *Xenopus* oocytes where the
46 subunit composition of the NMDA receptors can be easily controlled. The study was
47 restricted to GluN2A and GluN2B-containing NMDA receptors as these subunits were found
48 to exhibit the highest expression among GluN2 subunit family and we did not evidence the
49 presence GluN3 in our hippocampal cultures. L-Theanine (500 μ M) was without effect *per se*
50 on *Xenopus* oocytes expressing GluN1/GluN2A or GluN1/GluN2B NMDA receptors (Figure
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5). However, L-Theanine potentiated glutamate-elicited currents by co-application and to a similar extent on both GluN1/GluN2A and GluN1/GluN2B expressing oocytes (Figure 5C). By itself, glycine (10 μ M) elicited a small response which was not sensitive to L-Theanine. Moreover, its co-agonist action was evidenced by recording large currents when co-applied with glutamate. Nevertheless, the currents obtained by co-applying L-Theanine and glutamate represented $19 \pm 8\%$ (n = 12) and $23 \pm 9\%$ (n = 11) of those elicited by glycine and glutamate co-application on GluN1/GluN2A and GluN1/GluN2B expressing oocytes, respectively. The difference between these fractions was not significant.

Characterization of the effects L-Theanine derivatives: D-Theanine, L and D- γ -N-propyl-Gln

L-Theanine derivatives were further synthesized by substituting the γ -N-ethyl moiety and by changing the chirality, *i.e.* from L to D, of the asymmetric carbon. Indeed, as observed for D-serine, a D-chirality of the asymmetric carbon is also accepted for co-agonist binding on the GluN1 subunit. Activity of derivatives was tested using them at the single concentration of 10 μ M on mature cultured hippocampal neurons. Among all the compounds synthesized, it appears that the γ -N-propyl derivative exerted excitatory properties on $[Ca^{2+}]_i$ in cultured hippocampal neurons as well as L-Theanine did. Therefore, three compounds were further synthesized and tested: D-Theanine, L- and D- γ -N-propyl-Gln. They all retained the properties of NMDA receptor co-agonist as observed for L-Theanine, *i.e.* the blockade by NMDA receptor antagonist MK-801 (Figure 6A, B, C), the dependency on extracellular Ca^{2+} (Figure 6D). In addition the $[Ca^{2+}]_i$ rises elicited by these L-Theanine derivatives were not observed in the presence of TTX (not shown). The direct comparison of the responses induced by these compounds at a single concentration of 10 μ M indicated that both the change of chirality and the γ -N-propyl substitution significantly enhanced the responses elicited by L-Theanine (Figure 6E and F).

Discussion

We demonstrate here that L-Theanine exerts an excitatory action on hippocampal neurons mainly by potentiating NMDA responses. L-Theanine had no detectable agonist effect on other glutamate receptors, *i.e.* non-NMDA ionotropic and phospholipase C-associated mGlu receptors. *Per se*, L-Theanine induced $[Ca^{2+}]_i$ only in mature hippocampal neurons. This effect of L-Theanine was completely blocked by a NMDA receptor antagonist, or by extracellular Mg^{2+} ions, and was dependent on the presence of extracellular Ca^{2+} ions. This strongly suggests that the increase in $[Ca^{2+}]_i$ elicited by L-Theanine solely involves the direct or the indirect activation of NMDA receptors. The fact that these effects were only seen on mature cultures of hippocampal neurons with functional excitatory synaptic transmission²¹ suggests an indirect action where L-Theanine behaves as co-agonist of NMDA receptors activated by endogenously released glutamate. Accordingly, blocking synaptic transmission by TTX fully prevented the L-Theanine response in mature hippocampal neurons. The fact that TTX partially reduced the NMDA response, suggests that glycine and/or D-serine may also be synaptically released from mature hippocampal neurons. However, the existence of residual intracellular calcium responses induced by NMDA in the presence of TTX in mature hippocampal cultures, or by NMDA alone in immature cultures also suggests the presence of extracellular endogenous co-agonist during recording, released from the cells by mechanisms independent from the synaptic activity. The co-agonist action of L-Theanine was directly confirmed by the enhancement of the NMDA induced $[Ca^{2+}]_i$ response when L-Theanine and NMDA were co-applied in the presence of TTX and by the inhibitory effect of the glycine NMDA receptor site antagonist, 7-chlorokynurenic acid, on L-Theanine-elicited $[Ca^{2+}]_i$ changes.

A similar result was obtained on the NMDA responses recorded on *Xenopus* oocytes expressing GluN1/GluN2A or GluN1/GluN2B NMDA receptors, suggesting that the effects of L-Theanine were not restricted to one subtype of the GluN2 subunits. L-Theanine thus behaves as 'conventional' NMDA receptor co-agonist, such as glycine or D-serine, which exert their positive action by acting on the GluN1 subunit. This is in agreement with a previous report showing that L-Theanine may bind the glycine binding site of NMDA receptors⁹. Nevertheless, L-Theanine was found to be a lot less potent than glycine or D-serine to exert its co-agonist effect at NMDA receptors.

In our hands, L-Theanine behaves as a partial agonist at the glycine binding site on NMDA receptors in hippocampal neurons. This action is, to some extent, contrasting with previous

1 finding demonstrating the interactions of L-Theanine with NMDA receptor-dependent
2 neurophysiological phenomena in the CA1 area of the hippocampus to improve cognition.
3 Indeed, long-lasting treatments with L-Theanine appear to decrease NMDA receptor-
4 dependent LTP, while it increases NMDA receptor-independent LTP^{22,23}. The opposite
5 would reasonably be expected from a positive modulation of NMDA receptor. Acute and
6 chronic administrations of L-Theanine may thus result in the occurrence of different
7 neuroplastic phenomena.
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13 The L-Theanine used for this study was synthesized in a new efficient two-step synthesis with
14 important improvements as compared to previous methods, including extraction from tea
15 leaves^{24,25} and enzymatic biosynthesis²⁶, which are both expensive and low yield methods.
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18 Indeed, under our optimized conditions, the amidification reaction proceeded smoothly.
19 Good-to-excellent conversion rates, higher yields and shorter reaction times were observed
20 using microwaves irradiations as a source of heating and activation²⁷. The reaction occurred
21 in solvent-free system when the corresponding amines were liquid in an environmentally-
22 friendly protocol without any chromatographic purification. This procedure also enabled us to
23 obtain the D-enantiomer of Theanine and L- and D- γ -N-propyl-Gln with high yields and
24 without any racemization. Moreover, this process can be easily translated for the production
25 of gram scale of these derivatives using for example the microwave activation by MiniFlow
26 200SS model (Sairem). In addition, this reaction enabled the synthesis of derivatives by
27 changing the alkyl moiety on the nitrogen in γ position, leading to L- γ -N-alkyl and D- γ -N-
28 alkyl derivatives. Among these compounds, the D- γ -propyl-Gln appeared to be more potent
29 than L-Theanine itself to elicit $[Ca^{2+}]_i$ changes on hippocampal neurons. These structural
30 modifications of the L-Theanine backbone may be helpful for characterizing its binding site
31 on NMDA receptors and testing whether or not it overlaps the glycine site on GluN1, as
32 suggested here. Studies of the crystal structure of NMDA receptors suggest however the
33 potential presence of many possible allosteric binding sites within the receptor²⁸.
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37 Furthermore, we show that novel modulators of NMDA receptors with potential therapeutic
38 activity may be derived from L-Theanine. Indeed, glycine site NMDA receptors partial
39 agonists as D-cycloserine and GLYX13, which binds GluN1 glycine site, have proved to be
40 beneficial in improving learning during ageing²⁹ and in the course of pathological states as
41 depression³⁰ or conditions associated with hypo function of NMDA receptors, such as
42 psychosis¹⁶. Many psychiatric diseases resulting from a reduced activity of NMDA receptors,
43 including psychosis¹⁹, can be mimicked in rodents by a reduction in NMDA receptor function
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1 schizophrenia model as observed by the rescue of sensorimotor gating defects assessed by
2 measuring pre-pulse inhibition (PPI) ¹⁴. Moreover, L-Theanine seems to enhance PPI in
3 humans ³², thereby confirming its potential psychotropic effect for curative perspective of
4 neurological diseases. Further behavioural experiments will hopefully confirm the beneficial
5 actions of these L-Theanine derivatives in vivo, and present this novel class of NMDA
6 modulators as therapeutic strategy to alleviate the symptoms of various
7 neurological/psychiatric diseases.
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Materials and methods

Chemistry

Melting points were obtained using a Büchi 510 capillary apparatus and were uncorrected. ¹H NMR spectra were recorded at 300 MHz and 75 MHz using a Bruker AC300 instrument, at 600 MHz using a Bruker AC600 instrument. Chemical shifts are quoted in parts per million and were referenced to the residual solvent peak. The following abbreviations used: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet. Coupling constants were reported in Hertz (Hz). High resolution mass spectra (HRMS) were recorded on micromass electrospray instrument with only molecular ion and other major peaks being reported. LC-MS identification was by electrospray on HPLC Waters Alliance 2690. Flash chromatography was carried out using E-Merck Silica Gel (Kieselgel 60, 230-400mesh) as stationary phase. Thin layer chromatography was carried out on aluminium plates pre-coated with Merck Silicagel 60F254 and were visualized by quenching of Ultra-Violet fluorescence, or by staining with a 10% methanol phosphomolybdic acid solution followed by heating. Analytic HPLC were performed on a Waters apparatus 717 plus autosampler with Millennium 32 program on SymmetryShieldTM RP₁₈ 3.5µm 2.1x20mm column and using linear gradient of ACN in H₂O with 0.1% TFA in 5min with 3mL/min flow. Analytical chiral HPLC experiments were performed on a unit composed of a Merck D-7000 system manager, Merck-Lachrom L-7100 pump, Merck-Lachrom L-7360 oven, Merck-Lachrom L-7400 UV-detector and Jasco OR-1590 polarimeter using Beckman Coulter System Gold 126 Solvent Module HPLC machine with column Chiralcel OD-RH (250x4.6mm) and water/acetonitrile solvent system or with Chiralpk AD-H (250x4.6mm) and hexane/isopropanol solvent system. Both columns are from Chiral Technologies Europe (Illkirch, France). Optical rotations were determined on a Perkin-Elmer 341 polarimeter in appropriate solvent (20°C, sodium ray). THF was distilled from sodium/benzophenone ketyl. Reagents were supplied from commercial sources (Sigma Aldrich, Fluka).

Z-L-Theanine synthesis

Two mmoles of substrate (Z-L-Glu(OCH₃)-OH or Z-L-Glu(OBzl)-OH) was weighed in 0.5–2.0mL microwave reactor. Ethylamine (12mmol, 2M in THF) was then added. The reactor was sealed and heated under microwaves irradiation at 80°C (800W) for 4h. Then, the suspension was dissolved in ethyl acetate and washed two times with concentrated NH₄Cl. The organic phase was dried over MgSO₄, and concentrated under reduced pressure. Z-L-

1 Theanine precipitated as white powder in Et₂O (20mL), was filtered and lyophilized. ¹H NMR
2 (300 MHz, DMSO): δ = 1.02 (t, ³J=7.3 Hz, 3 H), 2.08 (m, 2 H), 2.17(m, 2 H), 3.24 (q,
3 ³J=7.29 Hz, 2 H), 4.43 (m, 1 H), 5.02 (s, 2 H), 5.71 (d, ³J=6.86 Hz, 1H), 7.28 (m, 5 H).
4 ¹³C NMR (75 MHz, DMSO): δ = 14.27, 25.73, 33.36, 37.22, 53.51, 67.6, 128.1, 128.31,
5 128.42, 135.09, 156.2, 171.59, 171.84. [α]_D²⁰: -11.0 (c=1, MeOH). MS (ESI): m/z 309.2
6 [M+H]⁺, 331.1[M+Na]⁺. Analytic Chiral HPLC: Chiralcel-OD column; H₂O/ACN (87/13),
7 0.6mL/min, 45min, 214 nm, tR= 30.15min.

8 Z-D-Theanine: [α]_D²⁰: 11.2 (c=1, MeOH). Analytic Chiral HPLC: Chiralcel-OD column;
9 H₂O/ACN (87/13), 0.6mL/min, 45min, 214nm, tR= 34.17min.

10 Z-L-γ-N-propylglutamine characterization

11 ¹H NMR (300 MHz, DMSO): δ = 0.82 (t, ³J=7.47 Hz, 3 H), 1.54(m, 2H), 1.90 (m, 2 H),
12 2.07(m, 2 H), 2.97 (t, ³J=7.09 Hz, 2 H), 3.71 (m, 1 H), 5.01 (s, 2 H), 6.61 (d, ³J=6.92 Hz, 1H),
13 7.28 (m, 5 H). ¹³C NMR (75 MHz, DMSO): δ = 11.32, 22.31, 28.75, 32.10, 40.27, 55.19,
14 65.04, 127.54, 127.63, 128.27, 137.21, 155.42, 172.05, 174.18. [α]_D²⁰: +2.5 (c=1, DMSO).
15 MS (ESI): m/z 323.2 [M+H]⁺, 345.1[M+Na]⁺.

16 L-Theanine characterization

17 Z-L-Theanine (0.36mmol, 100mg) was dissolved in freshly distilled THF (3ml) and 20%
18 Pd(OH)₂/C (20mg) added. The mixture was hydrogenated (H₂) at r.t. for 8h. Pd(OH)₂/C was
19 filtered off on celite and THF was removed under reduced pressure. L-Theanine was obtained
20 in quantitative yield as a white powder. ¹H NMR (300 MHz, D₂O): δ = 1.08 (t, ³J=7.32 Hz, 3
21 H), 2.11 (dd, ³J=7.77 Hz, ³J=6.16 Hz, 2 H), 2.39(m, 2 H), 3.17 (q, ³J=7.32 Hz, 2 H), 3.74 (t,
22 ³J=6.16 Hz, 1 H). ¹³C NMR (75 MHz, D₂O): δ = 13.41, 26.53, 31.73, 34.57, 53.56, 173.95,
23 174.29. [α]_D²⁰: + 8.4 (c=1, H₂O) [α]_D²⁰ litt: + 8.1 (c=5, H₂O). Mp = 215-219°C. MS (ESI):
24 m/z 175.1 [M+H]⁺, 197.1 [M+Na]⁺. HRMS calcd for C₇H₁₄N₂O₃ m/z [M+H]⁺ 175.1004
25 found 175.1039. D Theanine: [α]_D²⁰: -8.3 (c=1, H₂O).

26 Commercially available L-Theanine from Sigma Aldrich: ¹H NMR (300 MHz, D₂O): δ = 1.10
27 (t, ³J=7.75 Hz, 3 H), 2.13 (dd, ³J=8.0 Hz, ³J=6.5 Hz, 2 H), 2.4(td, ³J=8.0 Hz, ³J=4.2 Hz 2 H),
28 3.2 (q, ³J=7.75 Hz, 2 H), 3.76 (t, ³J=8.0 Hz, 1 H).

29 L-γ-N-propylglutamine characterization

30 ¹H NMR (300 MHz, D₂O): δ = 0.82 (t, ³J=7.43 Hz, 3 H), 1.45 (td, ³J=7.24 Hz, ³J=6.96 Hz, 2
31 H), 2.05 (m, 2H), 2.31(m, 2 H), 3.08 (t, ³J=6.96 Hz, 2 H), 3.64 (t, ³J=6.1 Hz, 1 H). ¹³C NMR
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1 (75 MHz, D₂O): δ = 10.63, 21.79, 27.21, 31.83, 41.33, 54.43, 174.75, 175.04. $[\alpha]_D^{20}$: +13.9
2
3 (c=1, H₂O). Mp = 207-209°C. MS (ESI): m/z 189.2 ($M+H$)⁺, 211.2 [$M+Na$]⁺. HRMS calcd
4 for C₇H₁₄N₂O₃ m/z [$M+H$]⁺ 189.1239 found 189.1239. D- γ -N-propylglutamine: $[\alpha]_D^{20}$: -14.0
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6 (c=1, H₂O).
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8 9 10 *HPLC measurement of Glutamate, GABA and L-Theanine*

11 Determination of Glutamate, GABA and L-Theanine involved the HPLC separation of
12 precolumn derivatized amino-acids, detected and quantified *via* fluorescence detection. The
13 chromatographic system consisted in a Dionex ASI-100 cooled autosampler, a Dionex P-680
14 pump, a Dionex TCC-100 oven and a Dionex RF-2000 fluorescence detector. Chromeleon
15 software 6.80 SP4 was used to drive the HPLC system and to integrate the signals obtained.
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18 Derivatization protocol was based on the method previously reported³³ with slight
19 modifications. Briefly summarized, 100 μ L of sample or standards in borate buffer (0.1M;
20 pH 9.3) were added to 20 μ L of potassium cyanide (KCN; 10mM in borate buffer) and 20 μ L
21 of Naphtalene-2,3-dicarboxaldehyde (NDA; 6mM in HPLC-grade methanol), either freshly
22 prepared or stored at 4°C in the dark (for less than a week). Reagents were thoroughly mixed in
23 the autosampler and the reaction was allowed to proceed, protected from light, at a
24 temperature of 6°C. After 20min, 20 μ L of the derivative was loaded into the HPLC system.
25 Separation was obtained using a Strategy C18 (150mm length x 3mm diameter, 3 μ m
26 granulometry) column (octadecyl 100Å porosity, 425m²/g, C18 end-capped silica with 19%
27 C) eluted and separated using an isocratic mobile phase containing Na₂HPO₄ (100mM), EDTA
28 (50 μ M) and HPLC grade MeOH (50:50), that was thoroughly filtered (Millipore 0.45 μ m
29 durapore) and continuously degased. Elution was performed at a rate of 0.8mL.min⁻¹ at a
30 constant 20°C in less than 12min. Emission of derivatives was measured at 480nm after
31 excitation at 420nm.
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45 *Materials for biological characterizations*

46 All experiments were carried out in accordance with the European Community Council
47 Directive of 24th November 1986 (86/609/ECC). Sprague–Dawley rats were from Janvier
48 Labs (France). Culture media (DMEM/Ham F12 with Hepes and 4.5 g/L glucose), Dulbecco's
49 phosphate-buffered saline (Dulbecco's PBS), Versene, antibiotics, and fetal calf serum (FCS)
50 were purchased from Invitrogen. Culture dishes were from Nunc. All chemicals were from
51 Sigma.
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Hippocampal neuron-enriched cultures

Primary neuronal cultures were established from 18-day-old embryonic rat hippocampi, as previously described^{34,35}, with minor modifications. After pre-incubation with Versene, hippocampal cells were mechanically dissociated and plated at a density of $2 \cdot 10^6$ cells/dish, on 8-well plates containing square ($10 \times 10 \text{ mm}^2$) glass coverslips, previously coated with poly-D-lysine ($50 \mu\text{g/mL}$) and then with DMEM/HAM F12 containing 10% FCS. Cells were grown in a defined medium containing DMEM/HAM F12, supplemented with 33mM glucose, 2mM glutamine, 100U/mL penicillin, $100 \mu\text{g/mL}$ streptomycin, 13mM sodium bicarbonate, $5.5 \mu\text{g/mL}$ transferrin, $10 \mu\text{g/mL}$ insulin, 1pM β -estradiol, 3nM triiodothyronine, 20nM progesterone, 5ng/mL sodium selenite, and $100 \mu\text{M}$ putrescine. Experiments were performed on cell cultures grown from 6 to 16 DIV.

Measurements of cytosolic-free Ca^{2+} concentration

Intracellular calcium concentration ($[\text{Ca}^{2+}]_i$) was measured with the fluorescent indicator fura-2³⁶. For this purpose, hippocampal cells grown on glass coverslips were loaded with fura-2 by a 30-min incubation at 37 C with $5 \mu\text{M}$ fura-2-AM and 0.02% Pluronic in the extracellular solution comprising: 124 mM NaCl, 3.5 mM KCl, 25 mM NaHCO_3 , 1.25 mM $\text{NaH}_2\text{-PO}_4$, 1 mM CaCl_2 , 2 mM MgSO_4 , 10 mM D-Glucose and 10 mM HEPES (bubbled with O_2/CO_2 : 95/5) pH 7.4. $[\text{Ca}^{2+}]_i$ was monitored by videomicroscopy. After rinsing, the glass coverslip was transferred to the recording chamber mounted on an inverted microscope (Leica, DMIRB). Fura-2 emission was obtained by exciting alternatively at 340 and 380 nm with a rotating filter wheel (Sutter Instruments) and by monitoring emissions (F340 and F380) at 510 nm. The ratio of emissions at 510 nm (F340/F380) was recorded in cells every second. Fluorescent signals were collected with a CCD camera (Hamamatsu), digitized, and analyzed with image analysis software (Acquacosmos, Hamamatsu). The coverslips were continually superfused with the extracellular solution thermostated at 37°C. Unless otherwise stated, experiments were carried in the absence of Mg^{2+} ions in the extracellular medium. Drug application was performed with a gravity-fed system and lasted 1min for each compound tested. Data are expressed as averages (\pm S.E.M) of the ratio between the fura-2 fluorescence values of 340/380 nm excitation wavelengths ratios (F340/F380) normalized to the corresponding basal F340/F380 measured prior to any drug application. Graphs presenting time-courses of F340/F380 ratio changes have been obtained by averaging data from a population of cells recorded individually during one single experiment. For a given determination, three individual experiments were at least performed on three independent cell

1 cultures. Therefore, the “n” values represent the entire population of cells recorded from at
2 least three independent cultures. One-way ANOVA followed by Dunn’s t-test was used for
3 multiple comparisons to determine significant differences between the experimental
4 determinations. Statistical analysis was performed with SigmaPlot 12.0 software. Values of
5 $p < 0.05$ were considered significant.
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10 *Xenopus oocytes injection and oocyte currents recording*

11 Xenopus oocytes were prepared and injected with in vitro transcribed RNA at $1\mu\text{g}/\mu\text{L}$ (20-
12 40nL) of rat GluN1-1a (named GluN1 herein) and rat GluN2A or mouse $\epsilon 2$ (named GluN2B
13 herein) with a stoichiometry of 1:1, as already been described 32. All constructions of NMDA
14 receptors subunits have been kindly provided by Pierre Paoletti (IBENS, ENS, Paris).
15 Macroscopic currents were recorded under two electrode voltage-clamp using a GeneClamp
16 500 amplifier (Axon Instruments) and analyzed in the ND96 HERG recording solution (in
17 mM: 96 NaCl, 3 KCl, 0.5 CaCl_2 , 5 Hepes, pH=7.2). Current and voltage electrodes (less than
18 $1\text{M}\Omega$) were filled with 3M KCl. Currents were filtered (20Hz) and digitized (66Hz) using a
19 Digidata-1200 interface (Axon Instruments). Data acquisition was done using version 7 of the
20 pClamp software (Axon Instruments).
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Figure legends

Figure 1: HPLC chromatograms of L-Theanine alone (dotted line) and of a mixture of L-Theanine, glutamate and GABA. The fluorescence of the derivatives was measured at 480nm after excitation at 420nm and is expressed in arbitrary units.

Figure 2: Characterization of the direct effects of L-Theanine on $[Ca^{2+}]_i$ in mature (about 2 weeks in vitro) cultured hippocampal neurons. **A:** Concentration-dependency of L-Theanine effect. L-Theanine was tested from 1 up to 100 μ M. On the left, an illustrative experiment in which 21 cells were recorded is shown. The concentration-dependent curve shown on the right have been obtained by measuring peak intensities of L-Theanine responses from $n = 45$ cells. **B:** Inhibitory effect of Mg^{2+} ions on L-Theanine-mediated responses. L-Theanine was tested from 10 μ M up to 1mM in the presence of Mg^{2+} ions (1mM) in the extracellular medium. As control, NMDA was tested in Mg^{2+} -free and Mg^{2+} -rich medium, as well as in the presence of the NMDA receptor GluN2B subunit antagonist ifenprodil (10 μ M) which completely inhibited NMDA-mediated responses. The graph represents an average of the $[Ca^{2+}]_i$ changes measured in 31 cells. This experiment has been performed on 60 cells in all. **C:** Dependency on NMDA receptor activity of L-Theanine responses. L-Theanine or NMDA were applied in the presence of the NMDA receptor non-competitive antagonist MK-801 (10 μ M). This antagonist exerted a reversible inhibition of the responses elicited by L-Theanine or NMDA. The graph was obtained by averaging F340/F380 ratios from 31 cells. This experiment has been performed on 70 cells in all.

Figure 3: NMDA receptor co-agonist action of L-Theanine on immature cultured hippocampal neurons. **A:** Lack of L-Theanine (10 μ M-1mM) effect on $[Ca^{2+}]_i$ in immature (6 DIV) cultured hippocampal neurons. NMDA (10 μ M) in combination with glycine (10 μ M) was tested as control. The graph has been obtained by averaging data from 29 cells. The experiment has been performed on 51 cells in all. **B:** Concentration-dependent potentiating action of L-Theanine (from 10 μ M up to 1mM) on the NMDA-mediated $[Ca^{2+}]_i$ increases in immature (6 DIV) hippocampal neurons. Glycine (10 μ M) was also tested as control. The graph was obtained by averaging data from 22 individual cells. **C and D:** Concentration-dependent potentiating action of glycine (**C**) and D-serine (**D**) on NMDA-mediated $[Ca^{2+}]_i$ increases in immature hippocampal neurons. Co-agonists were tested in the concentration range of 10nM up to 10 μ M. Data are from 24 and 26 cells, for glycine and D-serine,

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respectively. **E:** Recapitulative graph of the potentiating actions of glycine, D-serine and L-Theanine on NMDA-mediated responses, as a function of the concentration of co-agonist applied. Data have been obtained from 82, 80 and 71 cells for glycine, D-serine and L-Theanine, respectively. Data are expressed as percentages of increase of NMDA-mediated responses. They were obtained by normalizing the difference of the peak amplitudes of NMDA responses measured either in the presence or in the absence of the co-agonist to the amplitude of the NMDA response in each respective cell recorded. **F:** Effect of L-Theanine (1mM) on $[Ca^{2+}]_i$ increases elicited by kainate (40 μ M) in 6 DIV cultured neurons. The graph was generated by averaging data obtained from 40 individual cells (n = 85 in all).

Figure 4: Dependency of the L-Theanine-mediated $[Ca^{2+}]_i$ increases on synaptic activity in mature hippocampal cultured neurons. **A:** $[Ca^{2+}]_i$ changes elicited by L-Theanine and by the NMDA receptor co-agonists, glycine and D-serine, in mature hippocampal cultures (15 DIV) measured either in the absence (open circles, 'control', 12 cells) or in the presence of tetrodotoxin (filled circles, 26 cells). TTX (500nM) was applied throughout the recording. Data obtained with each protocol were superimposed. The experiments with or without TTX were performed on n = 50 and 47 cells in all, respectively. **B:** Co-agonist action of glycine, D-serine and L-Theanine on NMDA receptors measured in the presence of TTX in mature neurons. The co-agonists were applied at 10 μ M in combination to 10 μ M NMDA, in the presence of 500nM TTX in the extracellular medium. The graph plots averaged data from 23 individual cells (n = 48 in all). **C:** Effect of 7-chlorokynurenic acid on the L-Theanine-mediated $[Ca^{2+}]_i$ changes. 7-chlorokynurenic (0,1 μ M) was applied 1min prior to the L-Theanine (10 μ M) application. The graph plots averaged data from 20 individual cells (n = 50 in all).

Figure 5: Co-agonist action of L-Theanine at GluN1/GluN2A and GluN1/GluN2B NMDA receptors. **A and B:** Currents evoked by successive applications or co-applications of 500 μ M L-Theanine, 10 μ M glycine and 100 μ M glutamate, were measured on *Xenopus* oocyte expressing NMDA receptors. Representative current traces of GluN1/GluN2A (**A**) and GluN1/GluN2B (**B**) reveal the co-agonist action of L-Theanine as well as that of glycine. **C:** Average potentiating effects of L-Theanine on GluN1/GluN2A and GluN1/GluN2B (left) and graphs showing the large dispersion of both L-Theanine and glycine responses for GluN1/Glu2A (middle) and GluN1/GluN2B (right).

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3 **Figure 6:** Activity of L-Theanine derivatives. **A-C:** Dependency on NMDA receptor activity
4 of D-Theanine-, L- γ N-propyl-Gln- and D- γ N-propyl-Gln-mediated $[Ca^{2+}]_i$ increases in mature
5 (16 DIV) neurons. The $[Ca^{2+}]_i$ increases mediated by 10 μ M D-Theanine (**A**), L- γ N-propyl-
6 Gln (**B**) or D- γ N-propyl-Gln (**C**) were challenged with MK-801 (10 μ M). NMDA (10 μ M) was
7 used as a control. **D:** Dependency on the presence of extracellular Ca^{2+} ions of the responses
8 elicited by L-Theanine and derivatives. **E:** Inhibitory effect of extracellular Mg^{2+} ions on the
9 $[Ca^{2+}]_i$ responses induced by L-Theanine and derivatives. **F:** Cumulative graph plotting peak
10 responses elicited by 10 μ M L-Theanine or derivatives on $[Ca^{2+}]_i$. Data were obtained from
11 $n = 199, 68, 222,$ and 114 cells for L-Theanine, D-Theanine, L- γ N-propyl-Gln and D- γ N-
12 propyl-Gln, respectively. Bars indicate that the differences between peak amplitudes were
13 statistically significant ($p < 0.001$, one way ANOVA followed by Dunn's test).
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24 **Acknowledgements:**

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26 encoding NMDA receptor subunits.
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30 **Author contributions**

31 M.R., S.B., M.R., J.G., P.C., M.V. and V.R designed experiments

32 F.S., M.R., M.R., M.-C. de J.F., J. G., C. C.-S., G.B., T.C., M.A., A.T., M.G., C.M., P.C.,
33 M.V. and V.R. performed experiments.
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36 M.R., M.R., J.G., P.C., M.V. and V.R wrote the paper
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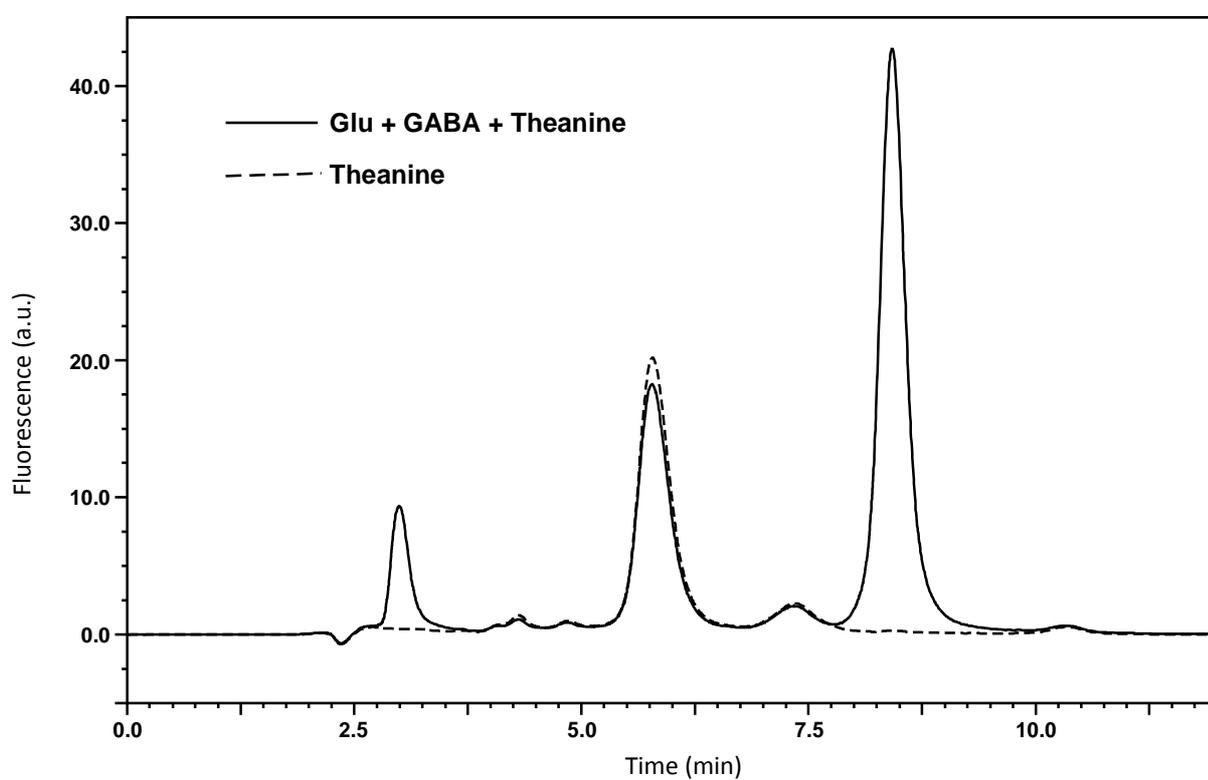
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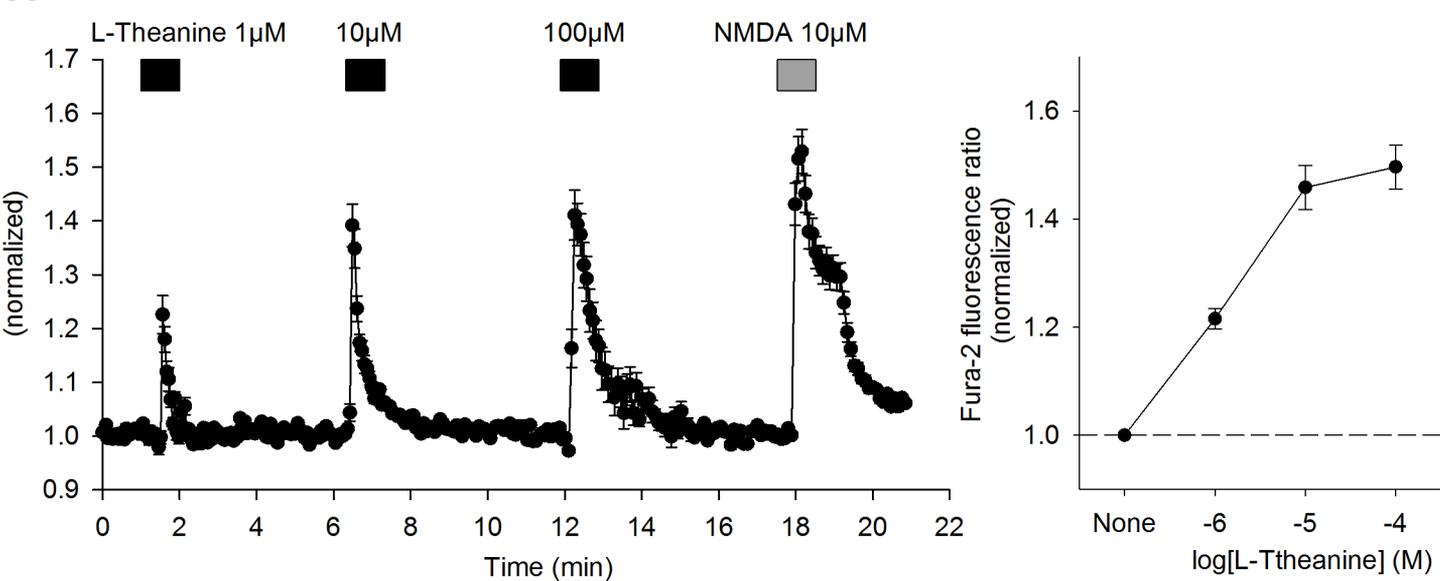
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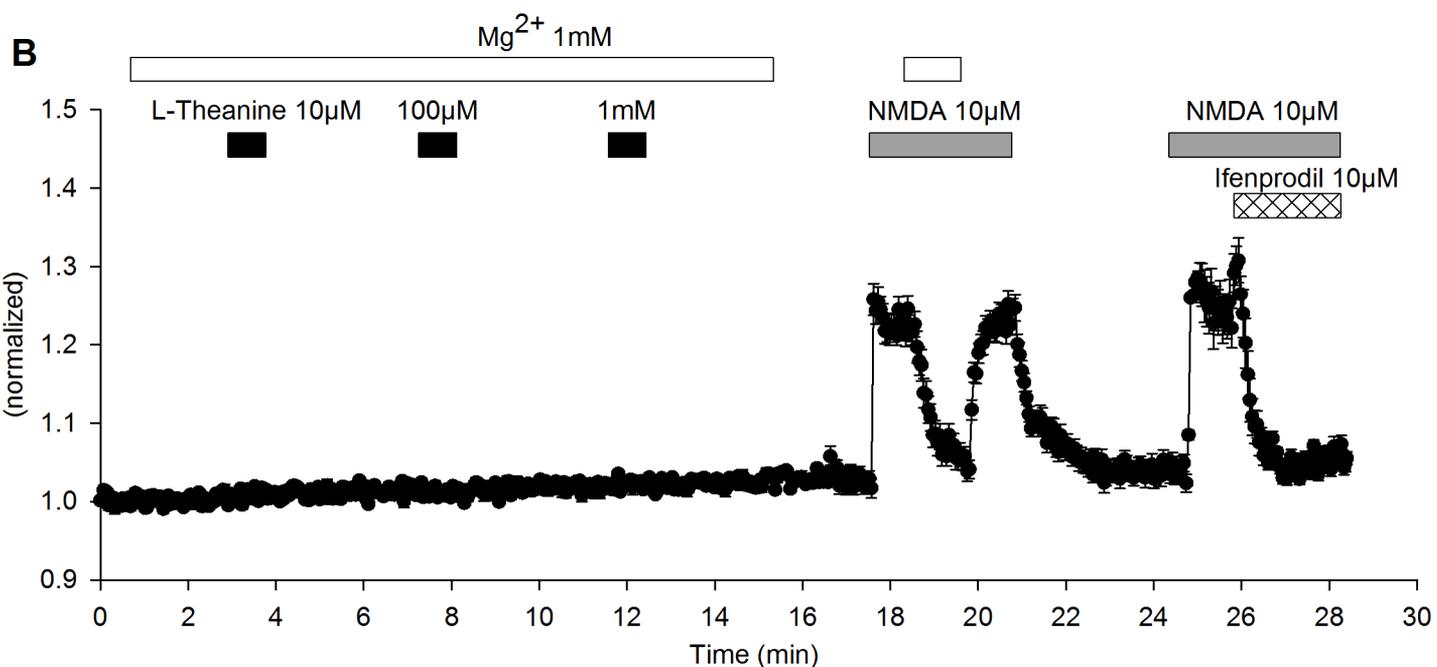
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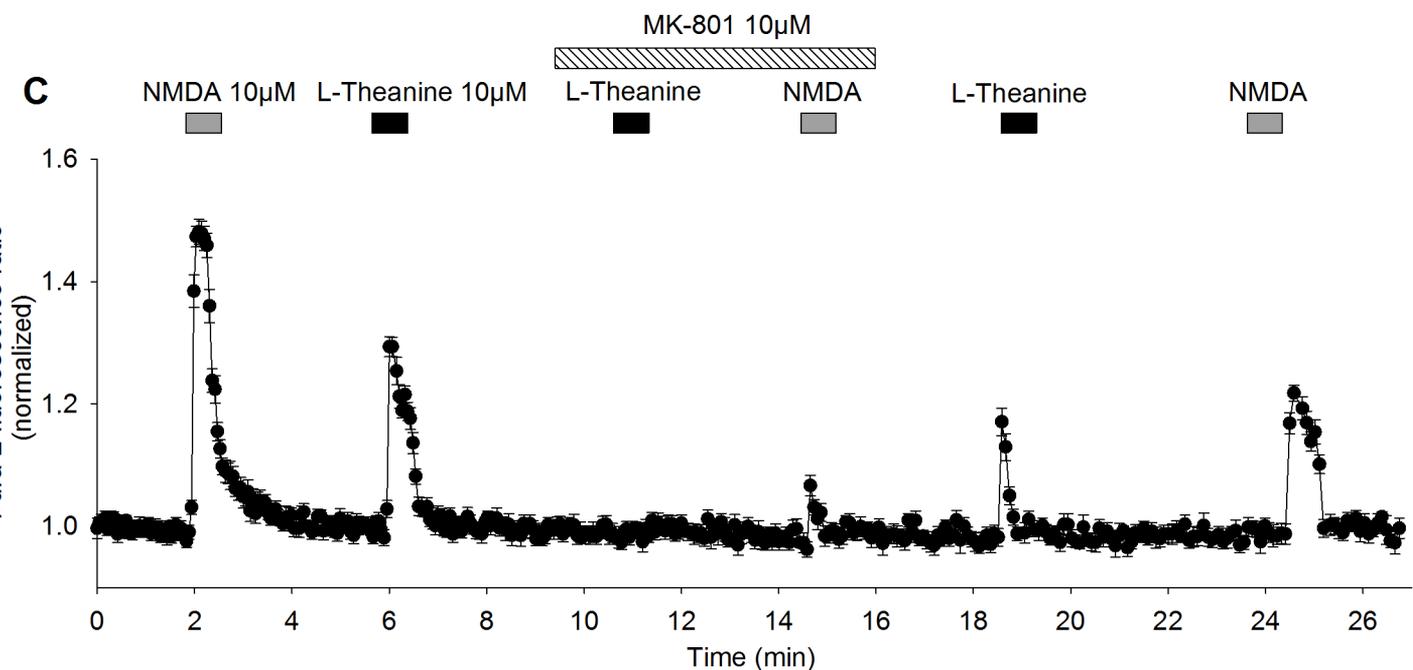
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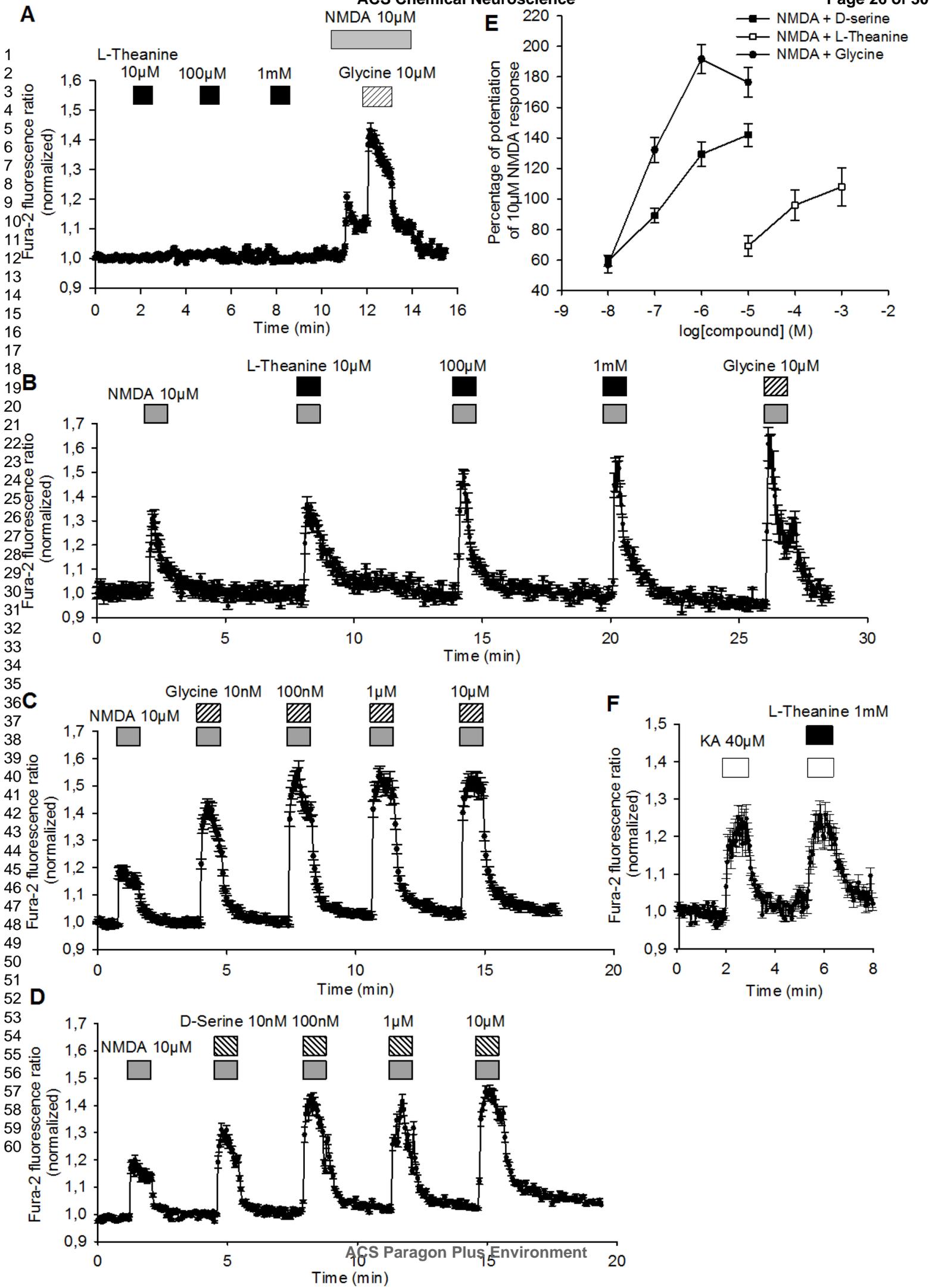


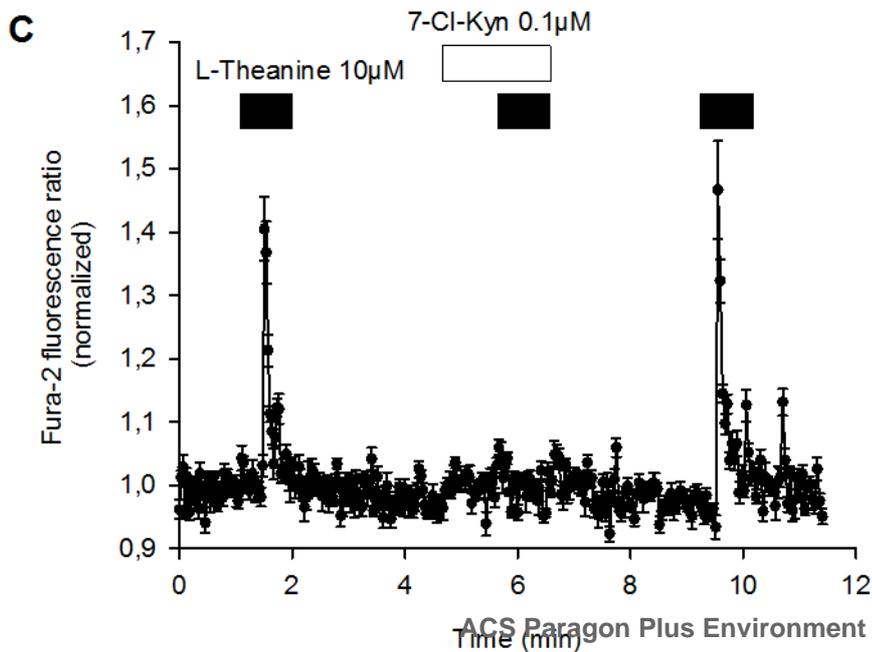
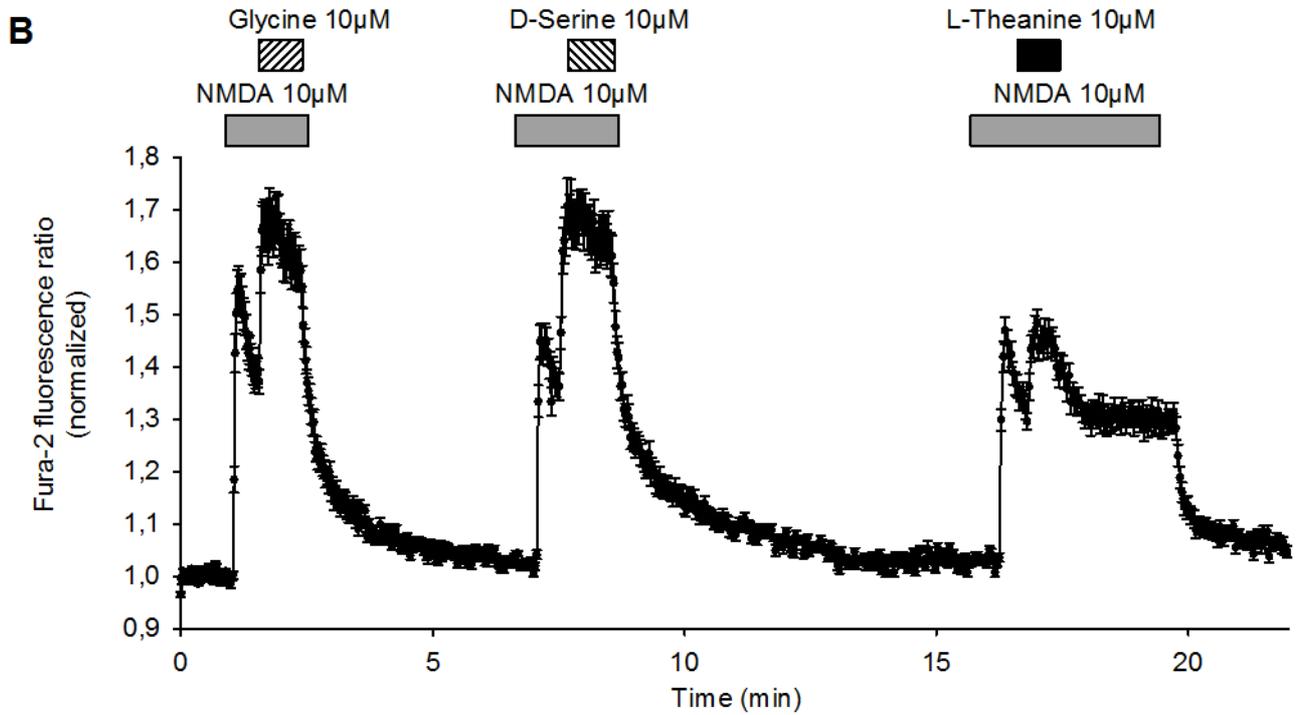
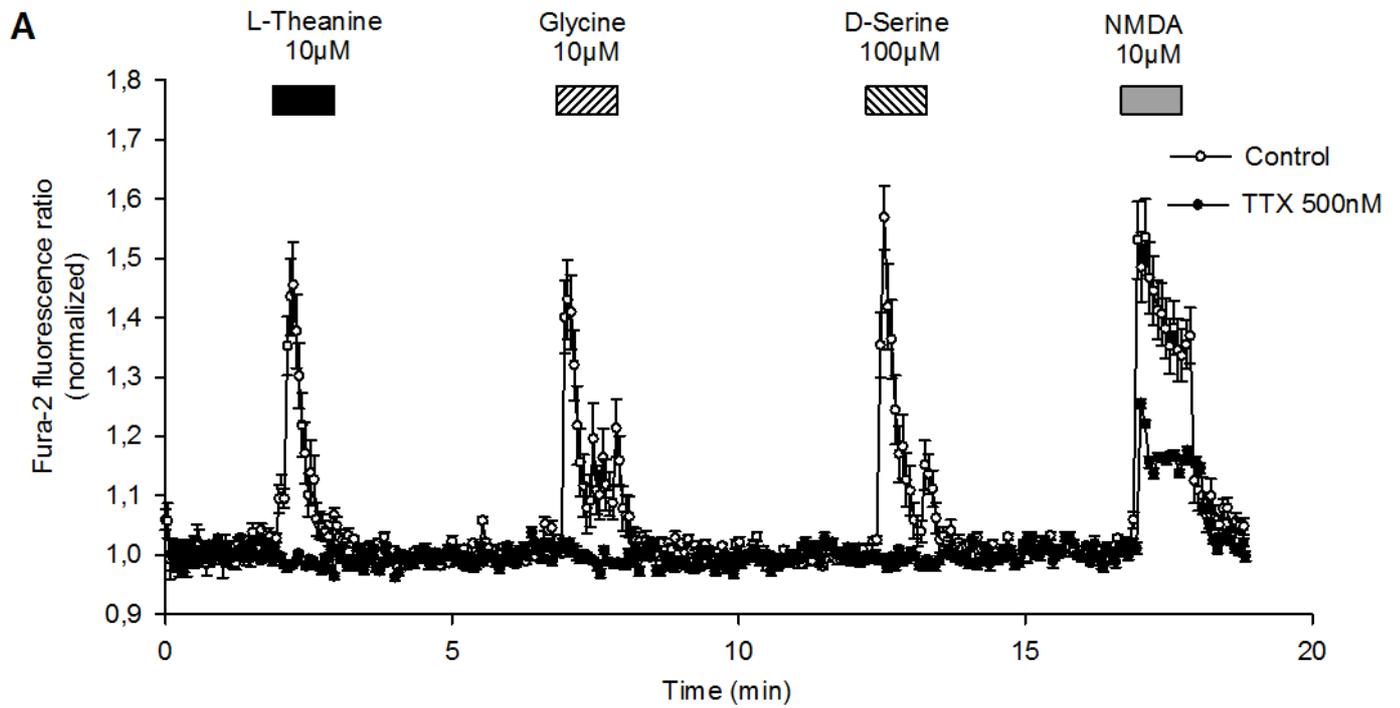
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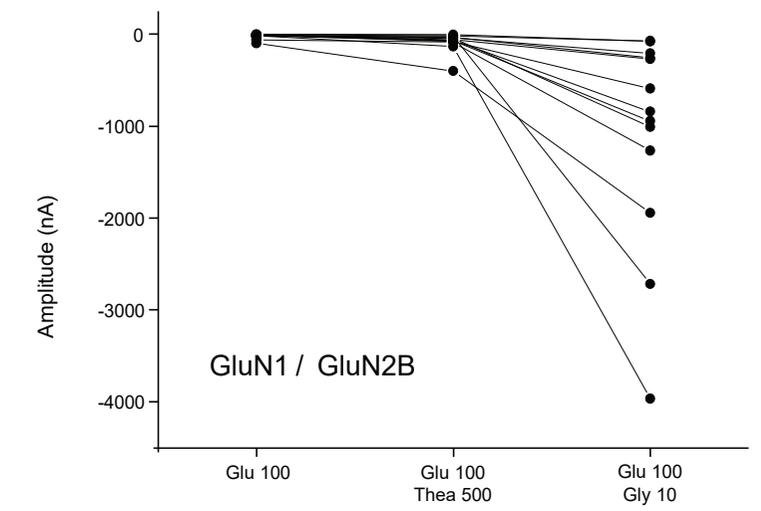
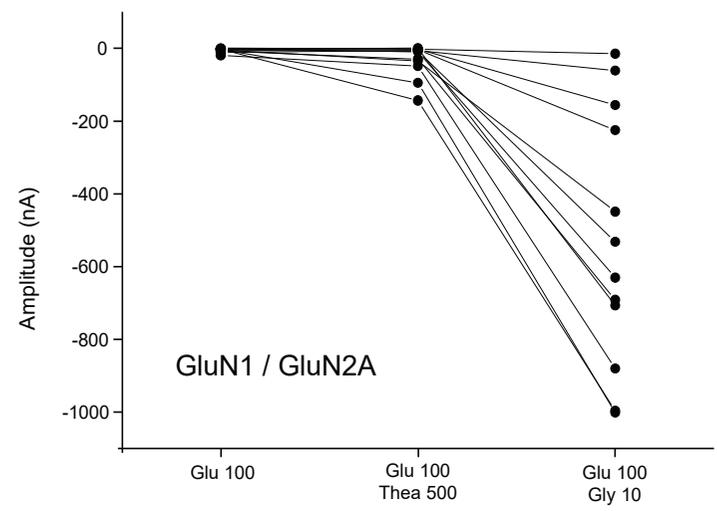
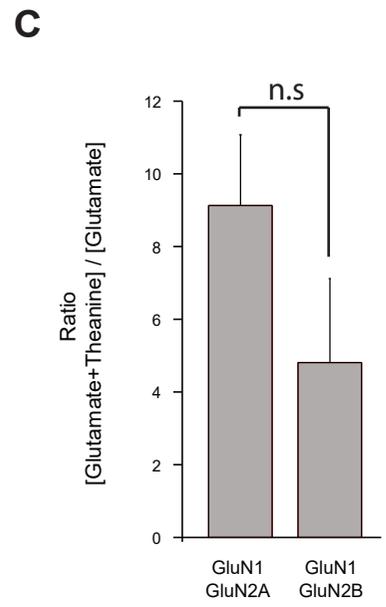
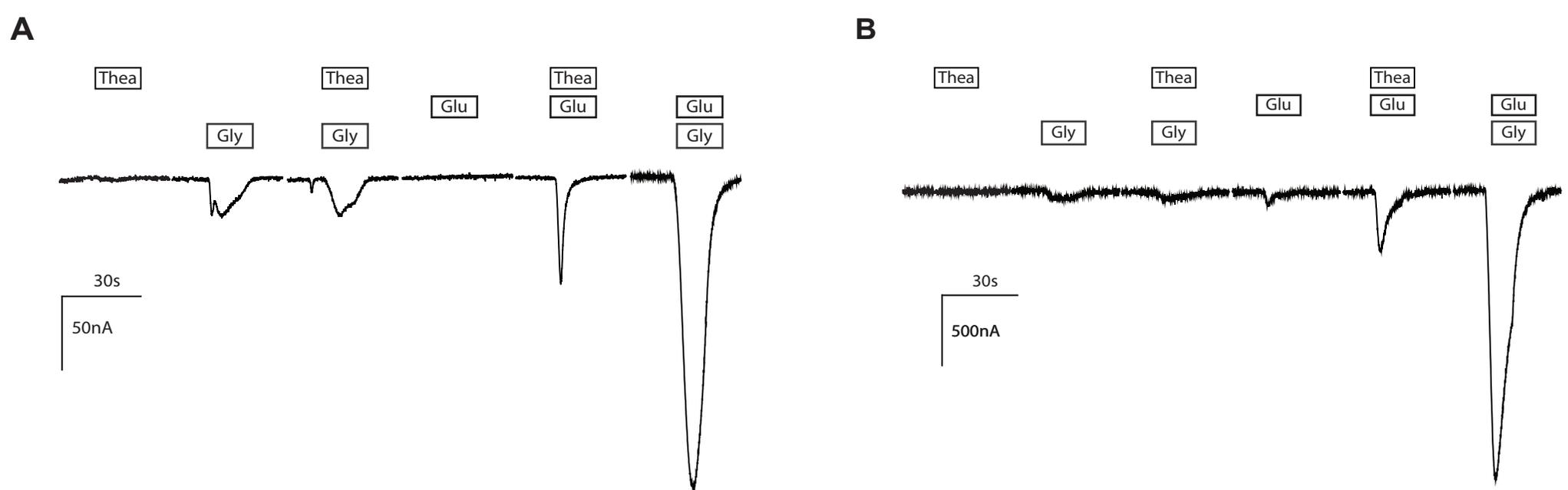


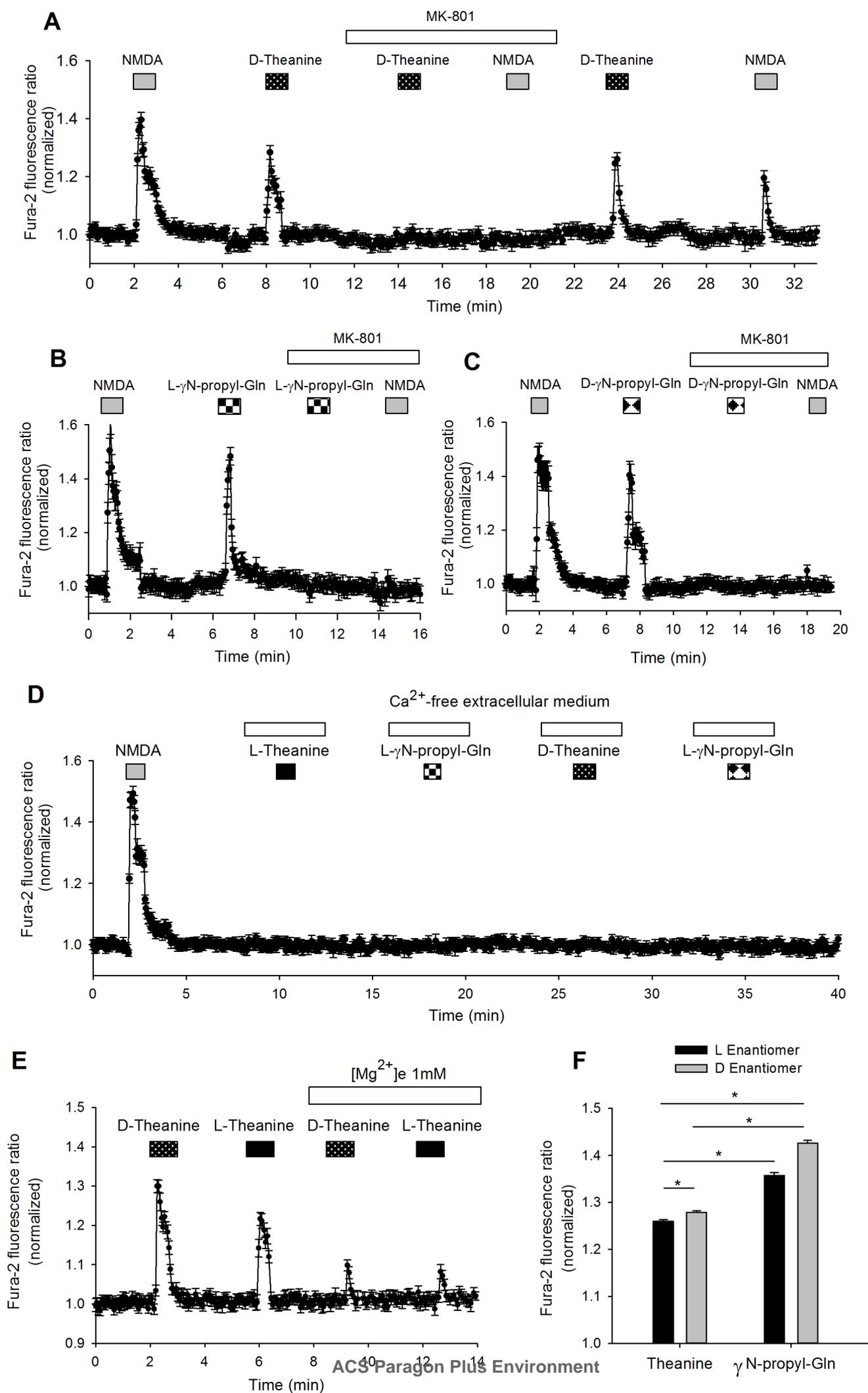
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Abstract Graphic

Synthesis and functional characterization of novel NMDA receptor modulators based on L-Theanine backbone:

