Structure–Activity Relationship Study of Selective Excitatory Amino Acid Transporter Subtype 1 (EAAT1) Inhibitor 2-Amino-4-(4-methoxyphenyl)-7-(naphthalen-1-yl)-5-oxo-5,6,7,8-tetrahydro-4H-chromene-3-carbonitrile (UCPH-101) and Absolute Configurational Assignment Using Infrared and Vibrational Circular Dichroism Spectroscopy in Combination with ab Initio Hartree–Fock Calculations

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ABSTRACT: The excitatory amino acid transporters (EAATs) play essential roles in regulating the synaptic concentration of the neurotransmitter glutamate in the mammalian central nervous system. To date, five subtypes have been identified, named EAAT1−5 in humans, and GLAST, GLT-1, EAAC1, EAAT4, and EAAT5 in rodents, respectively. In this paper, we present the design, synthesis, and pharmacological evaluation of seven 7-N-substituted analogues of UCPH-101/102. Analogue 9 inhibited EAAT1 in the micromolar range (IC50 value 20 μM), whereas analogues 8 and 10 were inactive (IC50 values >100 μM). The diastereomeric pairs 11a/11b and 12a/12b were separated by HPLC and the absolute configuration assigned by VCD technique in combination with ab initio Hartree−Fock calculations. Analogues 11a (RS-isomer) and 12b (RR-isomer) inhibited EAAT1 (IC50 values 5.5 and 3.8 μM, respectively), whereas analogues 11b (SS-isomer) and 12a (SR-isomer) failed to inhibit EAAT1 uptake (IC50 values >300 μM).

INTRODUCTION

In the central nervous system (CNS), the excitatory amino acid transporters (EAATs) are responsible for the uptake of the major excitatory neurotransmitter (S)-glutamate (Glu) from the synaptic cleft into glial cells and neurons. Thus, the EAATs are key players in the maintenance of synaptic as well as extrasynaptic Glu concentrations below levels of neurotoxicity.1 To date, five subtypes have been identified, named EAAT1−5 in humans, whereas they are termed GLAST, GLT-1, EAAC1, EAAT4, and EAAT5, respectively, in rodents. The five EAAT subtypes exhibit distinct expression patterns in the CNS: while EAAT1−3 (GLAST, GLT-1, and EAAC1, respectively) are expressed throughout the CNS, the EAAT4 subtype is expressed exclusively in Purkinje cells of the cerebellum and EAAT5 only in the retina.2 At the cellular level, EAAT1,2 are expressed predominantly in glia cells and astrocytes, whereas EAAT3,4 are expressed almost exclusively in neurons.3 Finally, EAAT1−3 are high-capacity Glu transporters, while EAAT4,5 are considered to be low-capacity Glu transporters, functioning primarily as Glu-gated chloride ion channels.3 Malfunction of the EAATs has been suggested to be a contributing factor in neurotoxic states and neurodegenerative diseases such as Alzheimer’s,4 Huntington’s,5 amyotrophic lateral sclerosis (ALS),6 cerebral stroke7, and epilepsy,1,8,9 as well as in psychiatric disorders like depression10 and schizophrenia.11,12

We have recently reported the first class of selective EAAT1 inhibitors and a first structure−activity-relationship (SAR) study.13,14 The analogues UCPH-101 and UCPH-102 were the

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most potent inhibitors in the series (IC$_{50}$ values 0.66 and 0.43 μM, respectively) (Figure 1). Comprising two chiral centers, all analogues in the series were synthesized and characterized pharmacologically as a mixture of four stereoisomers (Figure 2), however, the inhibitory activity resides in only two of these. In this paper, we present the elucidation of the stereochemical configuration in correlation with inhibitory activity for this new class of selective EAAT1 inhibitors.

**RESULTS AND DISCUSSION**

**Design and Synthesis.** The synthesis of the UCPH-101/102 compound class (Figure 1) is in general terms carried out by a three-component reaction (Figure 2). The R$^1$ substituent in the 7-position of the parental skeleton C originates from diketone A, whereas the R$^2$ substituent is derived from aldehyde B.

The previously reported SAR study of UCPH-101 and UCPH-102 concluded that the presence of an aromatic ring in the 7-position (R$^1$) is essential for inhibitory activity and that a 1-naphthyl group (UCPH-101 and UCPH-102) is superior (Figure 1 and Figure 2). On the other hand, the 4-position (R$^2$) was found to be able to accommodate substituents of various sizes, not being restricted to aromatic moieties (compounds 4–5, Figure 1). Furthermore, two methyl groups or no substituent in the 4-position was observed to result in complete loss of inhibitory activity at EAAT1 (compounds 4–5, Figure 1). In regard to the stereochemical configuration at the 4 and 7-positions, an in silico study concluded that the stereochemical configuration at C7 (R$^1$) has little influence on the spatial orientation of the substituent, whereas the substituent at 4-position (R$^2$) adapts distinct spatial orientation on inverting the stereochemistry (Figure 3). This finding is intriguing, and together with the fact that 4,4-dimethyl analogue 4 is inactive allowed for the conclusion that the stereochemical configuration at C4 is essential for inhibitory activity. To elucidate the stereochemical requirements for inhibitory activity, desymmetrization of the diketone fragment by introduction of a heteroatom seemed as an attractive approach. Starting with the enantiopure keto-lactam, a diastereomeric pairs of the final products 6 or 7 would be obtained. Following separation by chromatography, the absolute configuration could be determined by X-ray crystallography. Unfortunately, lactam 6 and lactone 7 were both without inhibitory activity at EAAT1.

To continue the objective, the strategy was modified as to introduce a nitrogen atom in the 7-position (Figure 4). By this tactic, the four stereoisomers is reduced to two, although it is unclear what the consequence of the presence of a basic nitrogen is for EAAT1 inhibitory activity. To elucidate the stereochemical requirements for inhibitory activity, desymmetrization of the diketone fragment by introduction of a heteroatom seemed as an attractive approach. Starting with the enantiopure keto-lactam, a diastereomeric pairs of the final products 6 or 7 would be obtained. Following separation by chromatography, the absolute configuration could be determined by X-ray crystallography. Unfortunately, lactam 6 and lactone 7 were both without inhibitory activity at EAAT1.
observation that a 7-benzyl group is allowed (Figure 2, compound 2). To broaden the SAR study further, analogue 10 was designed comprising an amide functionality in the 7-position. The two pairs of diastereomers, 11a/11b and 12a/12b, comprising an enantiomerically pure substituent in the 7-position (R1), were designed to resemble benzyl analogue 2 (Figure 2). The diastereomeric mixtures 11a/b and 12a/b were planned to be separated by HPLC and subsequently the absolute stereochemistry assigned by X-ray crystallography or IR/VCD investigations.

The synthesis of the 7-N-analogues was to be carried out by the three component reaction already described (Figure 1). Thus the synthesis of aminodiketone D comprising the appropriate N-substituent was to be pursued first and subsequently react it with 2-benzylidemalononitrile (13) to afford the final product, compounds 8−12b (Figure 5).3,13

The synthesis of target structure 7-N-phenyl 8 commenced with the synthesis of secondary amine 14 by N-alkylation of commercially available aniline and ethyl 2-bromoacetate in 46% yield (Scheme 1).17 Subsequently, N-alkylation of 14 with chloroacetone, NaI, and K2CO3 in THF afforded tertiary amine 15 in 31% yield.

With tertiary amine 15 in hand, reaction with t-BuOK in THF afforded diketone 16. Because 16 was found to be unstable on contact with silica,18 crude 16 was immediately converted to the target compound 7-N-phenyl 8 upon reaction with 1313 (Scheme 1).

The synthesis of 7-N-benzyl 9 (Scheme 2) followed the same strategy as for 8. Diketone 19, also decomposed on silica gel,18 thus crude 19 was converted directly into 7-N-benzyl analogue 9 in 57% yield (Scheme 2).

The synthesis of 7-N-benzylo analogue 10 was first explored by N-debenzylation of 9. However, all attempts failed (BzCl, Pd/C and H2 (g), Pd/C, H2 (g) and TFA, Pd/C, H2 (g) and concd HCl) at room temperature and atmospheric pressure were tried.19,20 Either full N-debenzylation was not achieved or a complex reaction mixture was obtained, including reduction of the two double bonds (observed by NMR).

Alternatively, N-debenzylation of tertiary amine 18 by hydrogenolysis gave the hydrochloride salt of secondary amine 20 in 97% yield (Scheme 3).20 Subsequently, amine 20 was reacted with benzoyl chloride and Et3N as base, in THF, 

Reagents and conditions: (a) DIEA, dry acetonitrile, 60 °C, 3 h, 46%; (b) chloroacetone, NaI, K2CO3, dry THF, 60 °C, 3 days, 31%, (c) t-BuOK, dry THF, 19 h; (d) 2-benzylidemalononitrile, piperidine, abs EtOH/H2O (3:1), 19 h, 51%.

Reagents and conditions: (a) dry THF, rt, 3.5 h, 90%; (b) chloroacetone, NaHCO3, abs EtOH, 60 °C, 18 h, 68%; (c) t-BuOK, dry THF, 17.5 h; (d) 2-benzylidemalononitrile, piperidine, abs EtOH/H2O (10:1), 24 h, 57%.
to give amide 21 in 88% yield. Cyclization of amide 21 using t-BuOK in THF afforded the unstable diketone 22, which was immediately converted to the 7-N-benzyol analogue 10 by condensation with 13\(^\text{13}\) (Scheme 3).

The synthesis of the diastereomeric pairs 11a/11b commenced with the preparation of amine 23 from alkylation of (S)-1-phenylethylamine with ethyl 2-bromoacetate.\(^\text{21}\) A second alkylation with chloroacetone afforded tertiary amine 24. Basic cyclization of tertiary amine 24 afforded crude diketone 25, which was condensed with 13\(^\text{13}\) to give a diastereomeric mixture of 11a/11b in a 1:1 ratio in overall 41% yield (Scheme 4). Separation of the diastereomeric mixture by chiral HPLC afforded enantiopure 11a and 11b. The synthesis of the diastereomeric pair 12a/12b followed the same strategy as for 11a/11b but with (R)-1-phenylethylamine as starting material. A diastereomeric mixture of 12a/12b was obtained in a 1:1 ratio in 58% yield, and separation by HPLC gave enantiopure 12a and 12b. To assign the stereochemical configuration at C4 of 11a/11b and 12a/12b, an X-ray crystallography study seemed attractive but it proved impossible to obtain crystals of 11a/11b or 12a/12b of sufficient quality.

**Vibrational Circular Dichroism (VCD) and Fast Fourier Transform Infrared (FTIR) Spectroscopy.** In combination with ab initio Hartree–Fock (HF) calculations, VCD is a valuable experimental method for the unambiguous assignment of absolute stereochemical configuration of chiral molecules.\(^\text{22}–\text{28}\) For reasons of compound quantities, it was decided to undertake 12a and 12b for IR/VCD study. The geometries of (S)-2-amino-5-oxo-4-phenyl-7-((R)-1-phenylethyl)-5,6,7,8-tetrahydro-4H-pyran[2,3-c]pyridine-3-carbonitrile (S1, Figure 6) and (R)-2-amino-5-oxo-4-phenyl-7-((R)-1-phenylethyl)-

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**Scheme 3. Reagents and Conditions for the Synthesis of 7-N-Benzyol Analogue 10**

Reagents and conditions: (a) Pd/C, concd HCl, H\(_2\)(g), abs EtOH, 2 h, 97%; (b) Et\(_3\)N, benzoyl chloride, dry THF, 14 h, 88%; (c) t-BuOK, dry THF, 2 h; (d) 13, piperidine, abs EtOH/H\(_2\)O (3:1), 26 h, 55%.

**Scheme 4. Synthetic Pathway Towards the Diastereomeric Pairs, 11a and 11b**

Reagents and conditions: (a) dry THF, rt, 2.5 h, 92%; (b) chloroacetone, NaHCO\(_3\), abs EtOH, 60 °C, 72 h, 21%; (c) t-BuOK, dry THF, 2 h; (d) 13, piperidine, abs EtOH/H\(_2\)O (10:3), 18 h, 41%.

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**Figure 6. Chemical structures of S1 and S2 as well as optimized geometries.**

5,6,7,8-tetrahydro-4H-pyran[2,3-c]pyridine-3-carbonitrile (S2, Figure 6) were optimized (low energy conformation) and used for calculation of IR (see Supporting Information) and VCD spectra (Figure 7).

The calculated IR spectra of S1 and S2 are for all importance similar (see Supporting Information). The absorption in the 2850–3000 cm\(^{-1}\) range is due to sp\(^3\) C–H stretching, whereas absorption over 3000 cm\(^{-1}\) is from sp\(^3\) N–H, sp\(^2\) C–H, and sp C–H stretching. The absorption peak at 2550 cm\(^{-1}\) originates from the triple bond of CN group, whereas the absorption in the 1450–2000 cm\(^{-1}\) is stretching, bending, and scissoring of alkanes, alkenes, aromatic rings, and ketones. The complexity of absorption in the 500–1450 cm\(^{-1}\) region (fingerprint region) makes it difficult to assign all of the absorption bands for S1 and S2 (see Supporting Information). Knowing the IR frequencies, the VCD spectra for S1 and S2 could be calculated (Figure 7).

The spectra show high similarity in the 3000–4000 cm\(^{-1}\) region (see Supporting Information), but a clear divergence was observed in the 1450–2000 cm\(^{-1}\) region (Figure 7). For S1, positive VCD bands at 1455 cm\(^{-1}\) (C–H and N–H bend) and 1814 cm\(^{-1}\) (C=O stretch) were observed, whereas negative VCD bands were observed for S2. Furthermore, at 1552 cm\(^{-1}\) (C=C, C–H, and N–H bend) a negative VCD band for S1 and a positive VCD band for S2 were observed.
Experimental IR spectra for 12a/12b were necessary to determine the possibility of measuring the VCD spectra in the desired interval (1500−2000 cm$^{-1}$) and to find the optimum IR intensity. The measured IR spectra for 12a/12b, using a fast transform infrared (FTIR) apparatus are depicted in figure 8.

To determine the optimal IR frequency, several solvents were tried out, of which DMSO gave the best result (Figure 8). Optimal conditions for the 1500−2000 cm$^{-1}$ region were shown to be a sample concentration of 150 mg/mL in DMSO at 8 cm$^{-1}$ resolution using a calcium fluoride cell and a 6 μm spacer (Figure 8A). Next, an IR temperature-dependent experiment was conducted for 12a at 30−50 °C, which confirmed that frequencies and absorbance were not critically influenced (Figure 8B). With these conditions in hand, VCD spectra for 12a/12b were measured using a FTIR apparatus.$^{25,29}$

Three major differences were observed from the calculated VCD spectra for S1 and S2 (Figure 7B). These three frequencies (1455, 1552, and 1814 cm$^{-1}$) have to multiply with 0.8929 to give the experimental frequencies (1299, 1385, and 1619 cm$^{-1}$), which thus can compare with the measured frequencies. Frequencies 1299 and 1385 cm$^{-1}$, in the fingerprint region, were not detected because the experimental VCD spectral range was 1500−2000 cm$^{-1}$. Thus only frequency 1619 cm$^{-1}$ was useful in determining the absolute configurations of 12a and 12b.

First, VCD spectrum of DMSO was measured and subtracted from the VCD spectra of 12a and 12b. However, no differences in the VCD spectra of 12a and 12b were observed, which was understandable because no IR signal was detected at 1500−2000 cm$^{-1}$ for DMSO. Fortunately, a positive VCD band was observed for 12a and a negative VCD band was detected for 12b at 1614 cm$^{-1}$ for two different concentrations (Figure 9A,B). A minor shift to lower frequency (1604 cm$^{-1}$) was observed at higher temperatures (Figure 9C,D). This shift in frequency was also detected in the IR spectra (Figure 8).

By comparison of the calculated VCD spectra with the experimentally determined, the stereochemistry of 12a and 12b could now be assigned. S1 and 12a both displayed a positive VCD band at 1614 and 1619 cm$^{-1}$, respectively, which unambiguously assigned the S,R-configuration to 12a. Analogue 12b displayed a negative VCD band at that frequency which
was in line with S2 and is thus assigned the RR-configuration (Table 1). The absolute configurations of 11a and 11b were assigned by comparison of melting points. Given the fact that enantiomers have the same melting point analogues 11a and 11b were assigned the RS- and SS-configuration, respectively (Table 1). Furthermore, comparison of HPLC retention times and NMR data confirmed this assignment.

**Pharmacological Characterization.** The seven 7-N-substituted analogues 8–12b were characterized pharmacologically at EAAT1–3 in a [3H]-d-Aspartate uptake assay (Table 2). 7-N-Phenyl analogue 8 displayed no significant inhibitory activity at EAAT1 at a concentration up to 100 μM. In comparison with 1, it can be concluded that nitrogen atom lonepair delocalization induces a disfavored spatial orientation of the phenyl group.

In comparison with 7-benzyl analogue 2, the 7-N-benzyl analogue 9 retained inhibitory activity at EAAT1 in the medium micromolar range (IC50 = 20 μM). This is explainable because free rotation of the benzyl groups is conserved. Interestingly, the N-benzoyl analogue 10 failed to inhibit EAAT1 mediated uptake (Table 2). The enantiopure analogues 11a and 12b displayed inhibitory activity at EAAT1 (IC50 values 5.5 and 3.8 μM, respectively), while 11b and 12a failed to inhibit EAAT1 uptake (Table 2). This confirmed the hypothesis that only one configuration at the 4-position was allowed for (Table 2). None of the synthesized analogues displayed any inhibitory activity at the RT-configuration (Table 1). The absolute configurations of 11a and 11b were assigned by comparison of melting points. Given the fact that enantiomers have the same melting point analogues 11a and 11b were assigned the RS- and SS-configuration, respectively (Table 1). Furthermore, comparison of HPLC retention times and NMR data confirmed this assignment.

**Figure 9.** Experimentally determined VCD spectra for 12a and 12b at different concentrations and temperatures. (A) VCD spectra at rt. for 12a (blue) and 12b (red) in DMSO (150 mg/mL). (B) VCD spectra of 12a (blue) and 12b (red) in DMSO (300 mg/mL) at rt. (C) VCD spectra of 12a (blue) and 12b (red) in DMSO (150 mg/mL) at 40 °C. (D) VCD spectra of 12a (blue) and 12b (red) in DMSO (150 mg/mL) at 50 °C. Arrows indicate the major differences in the VCD bands for 12a and 12b.

**Table 1. Melting Point and the Absolute Configuration of Chiral Analogues 11a–12b**

<table>
<thead>
<tr>
<th>entry</th>
<th>melting point [°C]</th>
<th>R/S isomer</th>
</tr>
</thead>
<tbody>
<tr>
<td>11a</td>
<td>121–123</td>
<td>RS</td>
</tr>
<tr>
<td>11b</td>
<td>102–104</td>
<td>SS</td>
</tr>
<tr>
<td>12a</td>
<td>121–123</td>
<td>SR</td>
</tr>
<tr>
<td>12b</td>
<td>102–104</td>
<td>RR</td>
</tr>
</tbody>
</table>

*Melting points were measured using a MPA 100 Optimelt automatic melting point system.*
Table 2. Pharmacological Characterization of 7-N-Substituted Compounds 8–12b as Inhibitors at EAAT1 in a [3H]-d-Aspartate Uptake Assay

<table>
<thead>
<tr>
<th>Compound no</th>
<th>R¹</th>
<th>R²</th>
<th>EAAT1 IC₅₀ [μM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>&gt;100 [4.0]</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>20 [4.79±0.07]</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>&gt;100 [4.0]</td>
</tr>
<tr>
<td>11a</td>
<td></td>
<td></td>
<td>5.5 [5.28±0.09]</td>
</tr>
<tr>
<td>11b</td>
<td></td>
<td></td>
<td>&gt;300 [3.5]</td>
</tr>
<tr>
<td>12a</td>
<td></td>
<td></td>
<td>&gt;300 [3.5]</td>
</tr>
<tr>
<td>12b</td>
<td></td>
<td></td>
<td>3.8 [5.43±0.06]</td>
</tr>
</tbody>
</table>

(Data are given as IC₅₀ values in μM with pIC₅₀ ± SEM in brackets. None of the synthesized analogues displayed inhibitory activity at EAAT2 or EAAT3 when applied at the highest possible concentrations (8, 10: IC₅₀ > 100 μM, 9, 11a, 11b, 12a, 12b: IC₅₀ > 300 μM).

**CONCLUSION**

In conclusion, seven 7-N-substituted analogues 8—12b of EAAT1-selective inhibitors UCPH-101/102 were designed and synthesized. The absolute configuration of enantiopure 11a, 11b, 12a, and 12b was assigned by use of VCD technique in combination with ab initio HF calculations. In an EAAT1 uptake assay, N-benzyl analogue 9 displayed inhibitory activity in the micromolar range (IC₅₀ = 20 μM), whereas the N-phenyl analogue 8 and N-benzyl analogue 10 displayed no EAAT1 inhibitory activity. Enantiopure 11a and 12b inhibited EAAT1 uptake in the low micromolar range (IC₅₀ values 5.5 and 3.8 μM, respectively), whereas their respective diastereomer 11b and 12a was inactive. These results allow for the conclusion that the R-configuration in the 4-position is essential for EAAT1 inhibitory activity. This insight may advance future design and synthesis of selective EAAT1 inhibitors.

**EXPERIMENTAL SECTION**

Chemistry. All reactions involving dry solvents or sensitive agents were performed under a nitrogen atmosphere and glassware was dried prior to use. Solvents were dried according to standard procedures, and reactions were monitored by analytical thin-layer chromatography (TLC, Merck silica gel 60 F₂₅₄ aluminum sheets). Flash chromatography was carried out using Merck silica gel 60A (35–70 μm). ¹H and ¹³C NMR spectra were recorded on a 300 MHz Varian Mercury 300BB in CDCl₃ using CHCl₃ as internal standard unless otherwise noted. MS spectra were recorded using LC-MS performed using an Agilent 6400 triple quadrupole mass spectrometer equipped with an electrospray ionization source. Gradients of 5% aqueous acetonitrile ≤0.05% formic acid (buffer A) and 95% aqueous acetonitrile +0.043% formic acid (buffer B) were employed. Analytical HPLC was performed using a Dionex Ultimate 3000 pump and photodiode array detector (200 and 210 nm, respectively) installed with a Zorbax SB 3.5 μm, 4.6 mm × 150 mm column, using a 5–95% MeCN gradient in H₂O containing 0.1% TFA. Melting points were measured using a MPA 100 Optimum automated melting point system. Optical rotation was measured using a Jasco DIP-370 digital polarimeter, with Na lamp (589 nm). All commercial chemicals were used without further purification. The purity of all tested compounds was determined by elementary analysis and HPLC to be >95%.

2-Amino-5-oxo-4,7-diphenyl-5,6,7,8-tetrahydro-4H-pyrano[2,3-c]pyridine-3-carbonitrile (8). A solution of ethyl 2-(2-oxopropyl)-phenylamino)acetate (15) (269 mg, 1.14 mmol) in dry THF (4 mL) was added dropwise over 10 min to a suspension of potassium tert-butoxide (192 mg, 1.71 mmol) in dry THF (5 mL) at 0 °C under N₂ atmosphere. The reaction mixture was stirred at rt for 15 h and quenched with satd NaHCO₃ (2 mL). After concentration in vacuo, the crude product was dissolved in EtOH/H₂O (8 mL, 3:1) and 13 (176 mg, 1.14 mmol) and piperidine (45 μL, 456 μmol) were added. The reaction mixture was stirred at rt for 19 h. The reaction mixture was concentrated with silica gel in vacuo and purified by column chromatography on silica gel to afford the title compound as a pale-yellow solid (200 mg, 581 μmol, 51% yield); Rf 0.31 (EtOAc/heptane 1:2). ¹H NMR (300 MHz, DMSO-d₆): δ: 7.26–7.08 (m, 9H), 6.98 (d, J = 9.0 Hz, 2H), 6.85 (t, J = 6.7 Hz, 1H), 4.46 (d, J = 17.1 Hz, 1H), 4.27 (s, 1H), 4.15 (d, J = 17.1 Hz, 1H), 4.03 (d, J = 17.4 Hz, 1H), 3.76 (dd, J = 17.1, 1.2 Hz, 1H). ¹³C NMR (75 MHz, DMSO-d₆): δ: 193.1, 162.7, 159.0, 149.3, 144.7, 130.0, 129.2, 128.1, 127.6, 120.9, 120.3, 116.6, 113.4, 59.1, 56.6, 48.6, 35.6; mp 203–205 °C (decomposed). LC-MS (m/z) calc'd for C₂₁H₁₇N₃O₂ [M + H⁺], 344.1; found, 344.1.

2-Amino-7-benzoyl-5-oxo-4-phenyl-5,6,7,8-tetrahydro-4H-pyrano[2,3-c]pyridine-3-carbonitrile (9). A solution of ethyl 2-(benzyl(2-oxopropyl)amino)acetate (18) (381 mg, 1.5 mmol) in dry THF (4 mL) was added dropwise over 15 min to a solution of potassium tert-butoxide (188 mg, 1.68 mmol) in dry THF (5 mL) at 0 °C under a N₂ atmosphere. The reaction mixture was stirred at rt for 18 h and quenched with satd NaHCO₃ (2 mL). After concentration in vacuo, the crude product was dissolved in abs EtOH (10 mL) and H₂O (1 mL) and 13 (150 mg, 1.1 mmol) and piperidine (20 μL, 216 μmol) were added. The reaction mixture was stirred at rt for 22 h and then concentrated with silica gel in vacuo and purified by column chromatography on silica gel. This afforded the title compound as a pale-yellow solid (224 mg, 619 μmol, 57% yield); Rf 0.20 (EtOAc/heptane 3:1). ¹H NMR (300 MHz, CDCl₃): δ: 7.34–7.18 (m, 10H), 4.53 (s, 2H), 4.42 (s, 1H), 3.65 (d, J = 3.0 Hz 2H), 3.48 (dd, J = 16.8, 0.9 Hz, 1H), 3.32–3.24 (m, 2H), 3.07 (dd, J = 16.2, 2.4 Hz, 1H). ¹³C NMR (75 MHz, CDCl₃): δ: 192.8, 161.2, 157.1, 143.2, 135.8, 129.1, 128.6, 128.5, 127.8, 127.6, 127.3, 118.3, 113.5, 63.6, 61.1, 60.5, 51.3, 34.9; mp 180–182 °C (decomposed). LC-MS (m/z) calc'd for C₂₃H₂₁N₂O₂ [M + H⁺], 358.1; found, 358.1.

2-Amino-7-benzyl-5-oxo-4-phenyl-5,6,7,8-tetrahydro-4H-pyrano[2,3-c]pyridine-3-carbonitrile (10). A solution of ethyl 2-(2-oxopropyl)benzamido)acetate (21) (350 mg, 1.32 mmol) in dry THF (10 mL) was added dropwise to a suspension of potassium tert-butoxide (224 mg, 2 mmol) in dry THF (8 mL) at 0 °C under a N₂ atmosphere. The reaction mixture was stirred at rt for 20 h and quenched with satd NH₄Cl (3 mL). After concentration in vacuo, the crude product was dissolved in EtOH/H₂O (12 mL, 3:1) and 13 (113 mg, 0.73 mmol) and piperidine (18 μL, 184 μmol) were added. The reaction mixture was stirred at rt for 26 h, concentrated with silica gel in vacuo, and purified by column chromatography on silica gel. The
A suspension of potassium tert-butoxide (78 mg, 0.69 mmol) in dry THF (5 mL) was added dropwise to a solution of Ethyl 2-(2-oxopropyl)amino)acetate (11a) (99.6% de): 124 mg, 0.46 mmol) in dry THF (8 mL) at 0 °C under a N2 atmosphere. The reaction mixture was stirred at rt for 2 h and quenched with satd NH4Cl (2 mL). After concentration in vacuo, the crude product was dissolved in EtOH/H2O (6.5 mL, 10:3) and 12a (300 mg, 0.55 mmol) and piperidine (11 mL) was added dropwise to a stirred solution of aniline (11a) (1 g, 5.6 mmol) and K2CO3 (2.31 g, 16.7 mmol) were stirred in dry THF (30 mL) at rt under a N2 atmosphere. A solution of chloroacetone (489 μL, 6.14 mmol) in dry THF (4 mL) was added dropwise to the reaction mixture and stirred for 30 min. Sodium iodide (290 mg, 1.64 mmol) was added, and the reaction mixture was stirred at 60 °C for 3 days. The crude reaction was quenched with H2O (10 mL) and extracted with EtOAc (3 × 30 mL), and the combined organic phases were washed with H2O (1 × 30 mL) and brine (1 × 20 mL). The organic phase was dried over MgSO4. After concentration, the crude product was purified by column chromatography on silica gel. This afforded the title compound as a pale-yellow oil (448 mg, 1.73 mmol, 31% yield); Rf 0.25 (EtOAc/heptane 1:2). LC-MS (m/z) calcd for C10H13NO2 [M + H+], 180.1; found, 180.1.

Ethyl 2-(2-Oxopropyl)amino)acetate (15a) Ethyl bromoacetate (2.43 mL, 22 mmol) was added dropwise over 2 h to a stirred solution of aniline (2 mL, 22 mmol) and N,N-dimethylpropylylamine (8 mL, 46 mmol) in acetonitrile (20 mL) at 60 °C. The reaction mixture was stirred for an additional 3 h at 60 °C and then concentrated to dryness. Addition of H2O (5 mL) to the residue and the solid was filtered and washed with H2O several times. Recrystallization from toluene afforded the title compound as a beige solid (1.83 mg, 10.1 mmol, 46% yield). H NMR (300 MHz, CDCl3) δ: 7.23–7.13 (m, 2H), 6.74 (t, J = 7.2, 1H, 2H), 4.23 (q, J = 7.2 Hz, 2H), 3.88 (s, 2H), 1.29 (t, J = 7.2 Hz, 3H). 13C NMR (75 MHz, CDCl3) δ: 171.1, 147.0, 129.2, 118.1, 61.3, 45.8, 14.2; mp 55–57 °C (decomposed). LC-MS (m/z) calcd for C11H14N2O [M + H+], 230.1; found, 236.1.

Ethyl 2-Benzylamino)acetate (17) A solution of ethyl bromoacetate (924 μL, 8 mmol) in dry THF (4 mL) was added dropwise over 10 min to a cooled solution of benzylamine (2 mL, 18 mmol) in dry THF (20 mL) at 0 °C under a N2 atmosphere. The reaction mixture was stirred for 3.5 h at rt, where after it was concentrated and resuspended in diethyl ether. The white solid was filtered off. The crude was concentrated and purified by column chromatography on silica gel. This afforded the title compound as a pale-yellow oil (1.45 g, 7.50 mmol, 90% yield); Rf 0.26 (EtOAc/heptane 1:2). 1H NMR (300 MHz, CDCl3) δ: 7.24–7.16 (m, 2H), 6.76 (dt, J = 7.2, 0.6 Hz, 1H), 6.53 (dd, J = 7.8, 0.9 Hz, 2H), 4.19 (q, J = 7.2 Hz, 2H), 4.12 (s, 2H), 4.09 (2H), 2.19 (s, 3H), 1.27 (t, J = 7.2 Hz, 3H). 13C NMR (75 MHz, CDCl3) δ: 207.7, 170.8, 147.7, 129.3, 118.3, 112.4, 62.3, 61.1, 53.8, 27.0, 14.2. LC-MS (m/z) calcd for C11H14N2O [M + H+], 236.1; found, 236.1.

Ethyl 2-(2-Benzylamino)acetate (18) Ethyl 2-benzylamino)acetate (17a) (165 mg, 853 μmol) and NaN3 (72 mg, 553 μmol) were stirred in abs EtOH (3 mL) at 60 °C under a N2 atmosphere. A solution of chloroacetone (68 μL, 553 μmol) in abs EtOH (1 mL) was added dropwise to the reaction mixture and stirred for 18 h. The crude reaction was quenched with H2O (5 mL) and extracted with EtOAc (3 × 10 mL), and the combined organic phases were washed with H2O (1 × 10 mL) and brine (1 × 10 mL). The organic phase was dried over MgSO4. After concentration in vacuo, the crude product was purified by column chromatography on silica gel to afford the title compound as a pale-yellow oil (137 mg, 580 μmol, 68% yield); Rf 0.51 (EtOAc/heptane 1:1). 1H NMR (300 MHz, CDCl3) δ: 7.34–7.20 (m, 5H), 4.15 (q, J = 6.9 Hz, 2H), 3.83 (s, 2H), 3.52 (s, 2H), 3.45 (s, 2H), 1.26 (t, J = 6.9 Hz, 3H). 13C NMR (75 MHz, CDCl3) δ: 207.8, 171.0, 138.1, 128.9, 127.4, 127.4, 127.3, 118.3, 113.4, 63.8, 63.6, 58.0, 49.7, 34.9, 19.3; mp 102–104 °C (decomposed). [α]24D +31.5° (c 0.23, abs EtOH). LC-MS (m/z) calcd for C12H15N2O2 [M + H+], 250.1; found, 250.1.
Ethyl 2-(2-Oxopropylamino)acetate (20). Ethyl 2-(benzyl[2-oxopropylamino]acetate (18) (1.19 g, 4.76 mmol) was stirred in abs EtOH (20 mL) at rt. under and a N2 atmosphere. Conc HCl (1 mL) and Pd/C (118 mg, 476 μmol) were added, and the reaction mixture was purged with H2 (g) for 2 h. The black solid material was filtered through Celite, and the residue was washed several times with abs EtOH. The filtrate was concentrated to afford the title compound as a beige solid (900 mg, 4.62 mmol, 97% yield). 1H NMR (300 MHz, MeOH-d4): δ: 4.30 (q, J = 6.9 Hz, 2H), 4.19 (s, 2H), 3.96 (s, 2H), 2.42 (s, 3H), 1.32 (t, J = 6.9 Hz, 3H). 13C NMR (75 MHz, MeOH-d4): δ: 172.2, 145.0, 128.9, 127.5, 127.1, 61.1, 163.0, 20.1, 14.1. LC-MS (m/z) calcd for C12H17NO2 [M + H+], 202.9; found, 202.9.

Ethyl 2-((2-Oxopropyl)(1-phenylethyl)amino)acetate (21). Ethyl 2-(2-oxopropyl)benzamido)acetate (21) (300 mg, 1.53 mmol) was stirred in dry THF (20 mL) at 0 °C under a N2 atmosphere. A solution of Et,N (446 μL, 3.22 mmol) in dry THF (2 mL) was added dropwise and stirred for an additional 5 min. A solution of benzoyl chloride (196 mL, 1.69 mmol) in dry THF (1 mL) was added dropwise, and the reaction mixture was stirred at rt for 14 h. The crude reaction was quenched with H2O (10 mL) and extracted with EtOAc (3 × 30 mL), and the combined organic phases were washed with H2O (1 × 20 mL) and brine (1 × 20 mL). The organic phase was dried over MgSO4 and concentrated in vacuo. The crude product was purified by column chromatography on silica gel to afford the title compound as a pale-yellow oil (354 mg, 1.35 mmol, 88% yield); Rf 0.29 (EtOAc/heptane 2:1). 1H NMR (300 MHz, DMSO-d6): δ: 7.30–7.19 (m, 18H), minor and m, SH, major), 4.30 (s, 2H, minor), 4.22 (s, 2H, major), 4.09 (s, 2H, minor), 3.99 (s, 2H, major), 2.12 (s, 3H, minor), 1.94 (s, 3H, major), 1.21 (t, J = 6.0 Hz, 3H, minor). 13C NMR (75 MHz, CDCl3, M = major conformer, m = minor conformer) δ: 202.9 (M and m), 172.2 (M and m), 169.3 (M and m), 134.7 (M), 130.2 (M and m), 128.6 (M and m), 126.8 (M), 126.6 (M), 161.6 (M), 61.3 (m), 59.6 (m), 59.6 (M), 51.8 (M), 47.4 (m), 27.4 (M), 27.0 (m), 14.1 (M and m). LC-MS (m/z) calcd for C12H17NO2 [M + H+], 208.1; found, 208.1.

(S)-Ethyl 2-(1-Phenylethyl)(1-phenylethyl)acetate (24). A solution of ethyl bromoacetate (1 mL, 9 mmol) in dry THF (4 mL) was added dropwise over 10 min to a cooled solution of (S)-1-phenylethylamine (2.41 mL, 19 mmol) in dry THF (25 mL) at 0 °C under a N2 atmosphere. The reaction mixture was stirred for 2.5 h at rt. After concentration in vacuo, the crude product was purified by column chromatography on silica gel. This afforded the title compound as a pale-yellow oil (432 mg, 1.61 mmol, 21% yield); Rf 0.13 (100% dichloromethane). 1H NMR (300 MHz, CDCl3) δ: 7.40–7.22 (m, SH), 4.17–4.08 (m, 3H), 3.57 (d, J = 5.4 Hz, 1H), 3.50 (d, J = 5.4 Hz, 1H), 3.43 (d, J = 4.2 Hz, 1H), 3.38 (d, J = 4.2 Hz, 1H), 2.11 (s, 3H), 1.34 (d, J = 6.9 Hz, 1H), 1.25 (t, J = 6.9 Hz, 3H). 13C NMR (75 MHz, CDCl3) δ: 208.8, 171.6, 143.9, 128.4, 127.4, 127.3, 61.6, 60.9, 60.4, 52.4, 27.5, 19.8, 14.2. LC-MS (m/z) calcd for C14H17NO2 [M + H+], 264.1; found, 264.1.

HPLC. Analytical HPLC for determination of the diastereomeric excess (de) was performed using a Chiralpak AD column (4.6 mm × 250 mm) equipped with a Chiralpak AD guard column (4 mm × 10 mm) (Daicel) and eluted at 1.0 mL/min with n-heptane/2-ProH (80:20). The column was connected to a Dionex Ultimate 3000 pump, a TSP AS-3000 autosample and a Dionex Ultimate 3000 photodiode array detector. For HPLC control, data collection and data handling, Chromelone software v. 6.80 was used.

Preparative HPLC. Separation of the diastereomeric mixtures was achieved using a Chiralpak AD column (20 mm × 250 mm) and flow rate 6 mL/min with n-heptane/2-ProH (80:20). Sample concentration was 6 mg/mL and injection volume was 2 mL.

IR and VCD. The IR was measured using a fast transform infrared (FTIR) apparatus. VCD spectra were measured using a FTIR apparatus with interferometers and with an IR source operating at Phi-M 400 Hz. A Nicolet Nexus 870 FT-IR spectrometer with the PEM module from Thermo Electron Corporation that has a wide spectral range from 200 to 7000 cm−1 was used. A sample concentration of 150 mg/mL in DMSO at 8 cm−1 resolution using a calcium fluoride (CaF2) cell and a 6 μm spacer gave an absorbance at 0.7. Calculated VCD frequencies using HF and 6-31G* basis set come out uniformly higher than experimental frequencies. Thus, a scaling factor of 0.8929 for harmonic vibrational frequencies is proposed as being appropriate for predictive proposes.31–33

In Silico Study. The modeling study was performed using the software package MOE (Molecular Operating Environment, Chemical Computing Group, 2010) using the built-in mmff94x forcefield and the GB/SA continuum solvent model. General procedure: The compound of interest was submitted to a stochastic conformational search (standard setup) to determine its low-energy conformation. Superimposition of selected low-energy conformations was done using the built-in function by fitting the three atoms amino groups and the C=O carbons of the phenyl rings.

Pharmacology. Cell culture of the EAAT1,2,3-HEK293 cell lines and the [H]-α-Aspptide uptake assay were performed essentially as previously described.30 The experimental procedures are described in detail in Supporting Information.

ASSOCIATED CONTENT

Supporting Information

IR and VCD values in table format for S1 and S2, as well as pharmacology experimental procedures. This material is available free of charge via the Internet at http://pubs.acs.org.

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The authors declare no competing financial interest.

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ABBREVIATIONS USED

ALS, amyotrophic lateral sclerosis; CNS, central nervous system; EAAC1, excitatory amino acid carrier subtype 1; EAAT(s), excitatory amino acid transporter(s); FTIR, Fast transform infrared; GLAST, glutamate aspartate transporter; GLT-1, glutamate transporter subtype 1; HF, Hartree–Fock;
HPLC, high-performance liquid chromatography; SAR, structure–activity relationship; VCD, vibrational circular dichroism

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