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Gain-of-function and loss-of-function variants in *GRIA3* lead to distinct neurodevelopmental phenotypes

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Abstract

AMPA (α -amino-3-hydroxy-5-methyl-4-isoxazole propionic acid) receptors (AMPA receptors) mediate fast excitatory neurotransmission in the brain. AMPARs form by homo- or heteromeric assembly of subunits encoded by the *GRIA1-GRIA4* genes, of which only *GRIA3* is X-chromosomal.

1 Increasing numbers of *GRIA3* missense variants are reported in patients with
2 neurodevelopmental disorders (NDD), but only a few have been examined functionally.

3 Here, we evaluated the impact on AMPAR function of one frameshift and 43 rare missense
4 *GRIA3* variants identified in patients with NDD by electrophysiological assays. Thirty-one
5 variants alter receptor function and show loss-of-function (LoF) or gain-of-function (GoF)
6 properties, whereas 13 appeared neutral.

7 We collected detailed clinical data from 25 patients (from 23 families) harbouring 17 of these
8 variants. All patients had global developmental impairment, mostly moderate (9/25) or severe
9 (12/25). Twelve patients had seizures, including focal motor (6/12), unknown onset motor (4/12),
10 focal impaired awareness (1/12), (atypical) absence (2/12), myoclonic (5/12), and generalized
11 tonic-clonic (1/12) or atonic (1/12) seizures. The epilepsy syndrome was classified as
12 developmental and epileptic encephalopathy in eight patients, developmental encephalopathy
13 without seizures in 13 patients, and intellectual disability with epilepsy in four patients. Limb
14 muscular hypotonia was reported in 13/25, and hypertonia in 10/25. Movement disorders were
15 reported in 14/25, with hyperekplexia or non-epileptic erratic myoclonus being the most
16 prevalent feature (8/25).

17 Correlating receptor functional phenotype with clinical features revealed clinical features for
18 *GRIA3*-associated NDDs and distinct NDD phenotypes for LoF and GoF variants. GoF variants
19 were associated with more severe outcomes: patients were younger at the time of seizure onset
20 (median age one month), hypertonic, and more often had movement disorders, including
21 hyperekplexia. Patients with LoF variants were older at the time of seizure onset (median age 16
22 months), hypotonic, and had sleeping disturbances. LoF and GoF variants were disease-causing
23 in both sexes but affected males often carried *de novo* or hemizygous LoF variants inherited
24 from healthy mothers, whereas all but one affected females had *de novo* heterozygous GoF
25 variants.

26

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5 **Running title:** Evaluation of *GRIA3* variants

6

7 **Keywords:** AMPA receptor; GRIA; GRIA3; clinical biomarker; genotype-phenotype

8 **Abbreviations:** agonist binding domain = ABD; α -amino-3-hydroxy-5-methyl-4-
9 isoxazolepropionic acid = AMPA; Dulbecco's modified Eagle's medium = DMEM; glutamate =
10 Glu; ionotropic glutamate receptors = iGluR; kainic acid = KA; neurodevelopment disorders =
11 NDDs; N-terminal domain = NTD; whole exome sequencing = WES; two-electrode voltage-
12 clamp = TEVC; transmembrane domain = TMD; C-terminal domain (CTD)

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9

10 **Introduction**

11 AMPARs belong to the ionotropic glutamate receptor (iGluR) superfamily of ligand-gated cation
12 channels¹. AMPARs are activated by glutamate (Glu) binding, which triggers the transient
13 opening of a central pore leading to a millisecond influx of cations, denoted excitatory
14 postsynaptic current (EPSC) that depolarizes the postsynaptic membrane and promotes neuronal
15 firing²⁻⁴. AMPAR-mediated EPSCs are essential components in most excitatory glutamatergic
16 signalling pathways, and normal AMPAR function is critical for most brain functions, including
17 learning and memory formation⁵⁻¹³. The assembly of GluA1-A4 subunits into homo- or
18 heterotetrameric receptor complexes forms diverse subtypes of AMPARs with distinct properties
19 and expression patterns^{14,15}. The GluA1-4 subunit proteins are highly similar and have a modular
20 architecture of two extracellular domains, the *N*-terminal domain (NTD) and the agonist binding
21 domain (ABD), a channel-forming transmembrane domain (TMD), and an intracellular carboxy-
22 terminal domain (CTD) of unknown structure (Fig. 1A). The bilobed ABD of each subunit
23 contains a single site where Glu binding initiates conformational changes that are transmitted via
24 semi-flexible linkers to the channel gate in the TMD. Rare genetic variants in the *GRIA1-4*
25 genes¹⁶⁻²¹ may disrupt AMPAR physiology and cause developmental and cognitive impairment,
26 behavioural, and psychiatric comorbidities, seizures, and cerebral malformations^{19,22-56}. *GRIA1*,
27 *GRIA2*, and *GRIA4* are autosomal genes, whereas *GRIA3* is located on the X-chromosome.
28 While pathogenic missense variants in *GRIA1*, *GRIA2*, and *GRIA4* appear to arise almost

1 exclusively *de novo*^{23,25,28}, pathogenic variants in *GRIA3* may be transmitted from healthy
2 mothers to affected male children, which is observed in several X-linked NDDs^{27,30}.

3 Currently, 20 *GRIA3* missense variants are reported in 30 patients, of whom four are
4 female^{22,26,27,29–35,38,46–49,55}. Of these variants, nine have been functionally tested, revealing or
5 suggesting loss-of-function (LoF) effects for seven variants detected in fifteen affected males
6 and in one female^{22,29,30,33,35} and gain-of-function (GoF) effects in two variants detected in one
7 female and one male^{32,34}. Thus, the phenotypic and genetic landscape in *GRIA3*-related disorders
8 remains ill-defined, lacking genotype-phenotype correlations or clinical biomarkers, particularly
9 in females.

10 We have therefore systematically interrogated the impact on GluA3-containing AMPAR
11 function of 44 rare inherited or *de novo* *GRIA3* variants identified in patients with NDD to assess
12 these for pathogenicity and establish LoF or GoF effects for overall receptor signalling function.
13 Also, for 25 patients with pathogenic LoF or GoF variants, we compared the clinical features
14 with the functional outcomes to identify genotype-phenotype correlations and clinical
15 biomarkers that could potentially predict the functional outcome of rare *GRIA3* variants. Our
16 results show that *GRIA3*-related disorders encompass two patient groups with distinct clinical
17 features that correlate with the GoF or LoF effect of the variant on receptor function. Also, our
18 findings expand the general knowledge of the pathogenic contribution of rare genetic alterations
19 in *GRIA3* to NDDs in the human population with diverse manifestations, influencing both the
20 timing of disease onset and main clinical symptoms.

21

22 **Materials and methods**

23 **Materials**

24 Unless otherwise stated, all chemicals were from Sigma-Aldrich (St. Louis, MO). Dulbecco's
25 modified Eagle's medium (DMEM), fetal bovine serum, trypsin, and penicillin-streptomycin
26 were from Invitrogen (Carlsbad, CA). DNA modifying enzymes were from New England
27 Biolabs (Ipswich, MA) except PfuUltra II Fusion HS DNA polymerase (Agilent, Carlsbad, CA).
28 Cyclothiazide (CTZ), kainic acid, and NASPM were from HelloBio (Bristol, UK).

1 **Molecular Biology**

2 *GRIA3* (MIM 138248) variants were introduced by site-directed mutagenesis into their
3 corresponding positions in cDNA expression constructs encoding GluA3. Specifically, the
4 plasmid vectors pXOOF and pCAGGS-IRES-EGFP containing cDNA for the unedited GluA3
5 flip and flop isoforms (GluA3_i and GluA3_o, respectively) were used for heterologous expression
6 in HEK293 cells or generation of mRNA for microinjection in *Xenopus laevis* oocytes (XOs).
7 For pCAGGS-IRES-EGFP, cDNA for GluA3_i and GluA3_o were subcloned into the *NheI* and
8 *XhoI* restriction sites of the vector. For pXOOF, the cDNA for GluA3_i was subcloned into the
9 *EcoRI* and *XhoI* restriction sites. For co-expression with GluA2, GluA2 was subcloned into the
10 vector pCAGGS-IRES-mCherry. Basepair changes in GluA3 were made by the overlapping PCR
11 method or the QuickChange mutagenesis kit (Stratagene, La Jolla, CA). Genetic changes were
12 verified by Sanger DNA sequencing of the entire GluA3 coding region (GATC Biotech,
13 Constance, Germany). When used as templates for *in vitro* transcription of mRNA, plasmid
14 constructs were linearized downstream of the 3' untranslated region using the restriction enzyme
15 *NheI*, column purified using NucleoSpin DNA clean-up kit (Macherey-Nagel, Düren, Germany),
16 and stored at a concentration of 1.0 µg/µL at -20 °C until use. cRNA transcription was performed
17 using the ARCA mRNA synthesis kit (NEB, Madison, WI, USA). The resulting mRNA was
18 purified using the NucleoSpin RNA Clean-up kit (Macherey-Nagel), diluted to 0.5 ng/nL, and
19 stored at -80 °C until use.

20

21 ***Xenopus laevis* oocyte preparation and injection**

22 Defolliculated XOs (stage V to VI) were prepared and injected with mRNA as described
23 previously⁵⁷. The care and use of *Xenopus laevis* animals strictly adhered to a protocol (license
24 2014-15-0201-00031) approved by the Danish Veterinary and Food Administration. Injected
25 XOs were incubated at 18 °C in Modified Barth's Solution (MBS) containing (in mM) 88 NaCl,
26 1 KCl, 0.41 CaCl₂, 2.4 NaHCO₃, 0.33 Ca(NO₃)₂, 0.82 MgSO₄, 5 Tris (pH 7.4) supplemented
27 with 50 µg/ml gentamicin until use. For expression of homomeric GluA3 receptors, XOs were
28 injected with 10 ng cRNA in a volume of 25 nL per oocyte and incubated for 3 days at 18 °C in

1 MBS until the experiment. For expression of heteromeric GluA2/A3 receptors, injection of 10 ng
2 of a 2:1 mix ratio of GluA2/GluA3 cRNA was used.

3

4 **HEK293 cell culturing and transfection**

5 HEK293T cells were cultured in a 37 °C incubator with 5% CO₂. Transfection was performed in
6 35-mm dishes using Lipofectamine2000 reagents (Invitrogen). For co-expression of GluA3 and
7 GluA2, the ratio of GluA3 to GluA2 cDNA was 1:1. The competitive antagonist NBQX (100
8 μM) was included in culture media to block receptor-induced cytotoxicity. Twenty-four hours
9 post-transfection, cells were dissociated with 0.05% trypsin, plated on coverslips pre-treated with
10 poly-D-lysine, and used for experiments 4 h after plating.

11

12 **Electrophysiology**

13 *Two-electrode voltage-clamp (TEVC) electrophysiology in XOs:* Glass micropipettes (0.69 mm
14 ID/1.2 mm OD, Harvard Apparatus, Holliston, MA) were pulled on a Sutter P-1000 micropipette
15 puller (Sutter Instruments, Novato, CA) to a tip resistance of 0.5-2.5 MΩ and filled with 3 M
16 KCl. Oocytes were clamped using a two-electrode voltage-clamp amplifier (OC-725C, Warner
17 Instruments, Hamden, CT) and continuously perfused with Frog Ringer's solution containing 115
18 mM NaCl, 2 mM KCl, 5 mM HEPES, and 1.8 mM BaCl₂ (pH 7.6) by gravity-assisted perfusion
19 at flow rates of 2 to 4 mL/min into a vertical oocyte flow chamber. Compounds were dissolved
20 in Frog Ringer's solution and added by bath application. Concentration-response data were
21 recorded at holding potentials in the -40 to -80 mV range. Each compound solution was applied
22 for 10 to 60 s depending on the time needed to obtain steady-state currents. Current signals were
23 low-pass filtered at 5 Hz using an USBPGF-S1 programmable instrumentation low-pass filter
24 (Alliagator Technologies, Cosa Meda, CA) and digitized with a sampling frequency of 10 Hz
25 using a CED 1401plus analog-digital converter (Cambridge Electronic Design, Cambridge, UK)
26 interfaced with a PC running WinWCP software (available from Strathclyde Electrophysiology
27 Software, University of Strathclyde, Glasgow, UK). Concentration-response experiments were
28 performed by measuring agonist-evoked current during stepwise application of increasing
29 concentrations of agonist, as illustrated in Fig. 3E. All experiments were performed at room

1 temperature. *Whole-cell voltage-clamp electrophysiology in HEK293 cells:* The deactivation and
2 desensitization kinetics of glutamate-evoked currents from WT and mutant GluA3 and GluA2/3
3 receptors were determined in the whole-cell configuration in HEK293 cells. After the formation
4 of whole-cell configuration, individual HEK293 cells were lifted with 3 to 5 MΩ borosilicate
5 glass pipettes filled with the following internal solution: 135 mM KF, 33 mM KOH, 2 mM
6 MgCl₂, 1 mM CaCl₂, 11 mM EGTA, 10 mM HEPES (pH 7.2). Glu (10 mM) was dissolved in
7 the extracellular solution: 140 mM NaCl, 2.5 mM KCl, 2 mM CaCl₂, 1 mM MgCl₂, 10 mM
8 HEPES, 5 mM Glucose (pH 7.2). Glutamate pulses of 1 or 500 ms were applied to cells using a
9 theta-glass pipette mounted on a piezoelectric bimorph driven by gravity. Glutamate-induced
10 currents were recorded using a MultiClamp 700B amplifier (Axon Instruments) with membrane
11 potential held at -70 mV. Current signals were recorded with an Axon Digidata 1440 data
12 acquisition system and with a sampling frequency of 100 kHz following low-pass filtration over
13 2 kHz. All experiments were performed at room temperature.

14

15 **Cohort**

16 Patients with inherited or *de novo* *GRIA3* variants were recruited through an international
17 collaboration with epilepsy and NDD research groups, the Leipzig GRI-registry
18 (<https://www.uniklinikum-leipzig.de/einrichtungen/humangenetik/Seiten/GRI-registry.aspx>),
19 Decipher⁵⁸, ClinVar⁵⁹, and via GeneMatcher⁶⁰. We also contacted the healthcare providers of
20 previously published patients to collect new or updated clinical information or used that
21 previously reported in the literature^{26,29,33,34,61} (seven patients). Clinical information was
22 collected by the local physicians or caregivers and included data on the age of seizure onset and
23 offset, seizure semiology, developmental trajectory, medical history, physical examination, EEG,
24 and neuroimaging. The study was conducted in agreement with the Declaration of Helsinki. The
25 Leipzig GRI-registry was approved by the local ethical committee; Leipzig/Germany (224/16-ek
26 and 379/21-ek). Since all probands were minors or had cognitive impairment, their parents or
27 legal guardians provided written informed consent.

28

1 **Data and statistical analysis**

2 Data for concentration-response curves were obtained from analysis of electrophysiological
3 recordings of agonist-evoked current responses using ClampFit 10 software (Molecular Devices,
4 San Jose, CA). Current responses were normalized to the current response by maximal agonist
5 concentration and used to construct composite concentration-response plots from at least 8
6 oocytes and fitted using GraphPad Prism v9 (GraphPad Software, San Diego, CA, USA) to a
7 four-variable Hill equation:

$$8 \quad \text{response} = \text{bottom} + \frac{\text{top} - \text{bottom}}{1 + 10^{(\log EC_{50} - X) \times nH}} \quad (\text{Equation 1})$$

9 where *bottom* is the fitted minimum response, *top* is the fitted maximum response, *nH* is the Hill
10 slope, *X* is the agonist concentration, and *EC₅₀* is the half-maximally effective agonist
11 concentration, respectively. The time constants for the rate of desensitization (τ_{desens}) and
12 deactivation (τ_{deact}) were obtained by fitting current responses evoked by 500 and 1 ms Glu
13 pulses with an exponential function using a non-linear least square algorithm (ClampFit):

14

$$15 \quad I = I1 \times \left(\exp\left(-\frac{\text{time}}{\tau1}\right) \right) + I2 \times \left(\exp\left(-\frac{\text{time}}{\tau2}\right) \right) \quad (\text{equation 2})$$

16

17 , where *I* is the total current amplitude, and *I1* and *I2* are the amplitudes of the fast and slow
18 current components, respectively, and $\tau1$ and $\tau2$ are the time constants for the decay of the fast
19 and slow current components. The weighted average τ was then calculated as follows:

$$20 \quad \tau_{\text{weighted}} = \left(\frac{I1 \times \tau1 + I2 \times \tau2}{I1 + I2} \right) \quad (\text{equation 3})$$

21 All desensitization time constants were determined using the two-component fitting, and τ_{desens} is
22 reported as the weighted average τ . Except otherwise stated, all deactivation time constants were
23 determined using mono-exponential fitting, using equation 2 with *I2* fixed at 0. Statistical
24 analyses of data were performed in GraphPad Prism 9. Unless otherwise stated, summary patch-
25 clamp and TEVC electrophysiology data are represented as mean with a 95% confidence interval
26 (CI). One-way analysis of variance (ANOVA) with Dunnett's post hoc multiple comparison test
27 was performed for comparisons of three or more groups in which the data were normally

1 distributed and where a P -value <0.05 was considered significant. For statistical analysis of
2 clinical data, quantitative statistics were analyzed using SPSS software (version 24, IBM, United
3 Kingdom). Two-sided T-test was used to determine the association of clinical features with the
4 LoF and GoF patient groups. P -value < 0.05 was considered significant. Unless otherwise stated,
5 the level of statistical significance is denoted as $*P < 0.05$, $**P < 0.01$, and $***P < 0.001$.
6 Extended statistical information including specific P -values are provided in the Supplementary
7 information.

8

9 **Results**

10 ***GRIA3* missense variants in NDD patients concentrate on domains** 11 **responsible for glutamate binding and channel gating**

12 To investigate the pathogenicity of *GRIA3* variants identified in NDD patients, we collected one
13 frameshift variant and 43 *GRIA3* missense variants identified in patients with presumed *GRIA3*-
14 related NDD (*Materials and methods*) (Fig. 1, Supplementary table S1). Notably, although the
15 central elements for channel function (the ABD, TMD, and ABD-TMD linkers) constitute less
16 than 50% of the GluA3 subunit protein, the majority of the *GRIA3* missense variants are located
17 in the ABD (15 variants), and TMD (13 variants) domains, and the ABD-TMD linkers (6
18 variants). In addition, none of these 34/43 variants are reported in the Genome Aggregation
19 Database (gnomAD), and *GRIA3* is predicted to be constrained to missense variants ($Z = 4.23$),
20 which indicates intolerance to missense variation, and the majority are predicted to be damaging
21 by *in silico* prediction of deleteriousness (Supplementary Table S1). In contrast, only 9 variants
22 affect residues in the NTD and CTD, which are non-critical domains for the core ligand-gated
23 channel function (Fig. 1A) (Supplementary Table S1).

24 ***GRIA3* variants have GoF or LoF effects on GluA3 receptor** 25 **function**

26 The majority of the identified *GRIA3* missense variants have not been functionally evaluated for
27 effects on GluA3-containing AMPAR function, except for variants p.(Arg450Glu),
28 p.(Ala615Val), p.(Arg631Ser), p.(Ala653Thr), p.(Arg660Thr), p.(Met706Thr), p.(Glu787Gly),

1 p.(Glu787Lys), p.(Gly826Asp), and p.(Gly833Arg)^{22,29,30,32-35}, although not in a systematic
2 manner. Therefore, we first evaluated all variants with TEVC electrophysiology to directly
3 compare effects, focusing on key receptor functional features that included current amplitude,
4 Glu sensitivity, receptor activation, and desensitization properties (Fig. 1B-C). Specifically,
5 *GRIA3* variants were introduced in cDNA encoding GluA3 and expressed in XOs as homomeric
6 receptors (*Materials and methods*). We first recorded current responses following the application
7 of a single high Glu concentration (300 μ M) with pharmacological blockade of receptor
8 desensitization (Fig. 1C). Twenty of the variants showed currents that were significantly lower
9 than WT, including nine variants with undetectable or very small (*e.g.*, 50-fold lower than WT)
10 current amplitude (Fig. 1B-C; Supplementary Table S2), indicating that these variants have
11 severe LoF effects on GluA3 subunit function or expression. The single frameshift variant
12 p.(Gln371Argfs*6) is located in the 5' end of the NTD-encoding segment of the *GRIA3* coding
13 sequence (Fig. 1A). Therefore, this variant results in the expression of only the NTD that cannot
14 form a functional receptor. Indeed, the expression of p.(Gln371Argfs*6) in XOs did not yield
15 any current response (Fig. 1C) and is assigned a complete LoF status. The remaining variants
16 produced current responses with amplitudes similar to or within two-fold range of WT (Fig. 1B
17 and C; Supplementary Table S2), except for the variants p.(Ala615Val), p.(Ser663Pro), and
18 p.(Gly803Glu), which showed more than two-fold significantly increased currents compared to
19 WT, suggesting an overall GoF effect on receptor function.

20 For all functional variants, we performed dose-response experiments with increasing
21 concentrations of Glu (Fig. 1D), and determined the half-maximally effective concentration
22 (EC_{50}) for receptor activation (Fig. 1E; Supplementary Fig. S2 and Table S3). As summarized in
23 Fig. 1B, 20 variants changed the EC_{50} significantly by more than two-fold. The most pronounced
24 changes were observed for the p.(Ser531Cys), p.(Ala654Thr), p.(Trp799Leu), and p.(Gly803Ala)
25 variants, which decreased EC_{50} more than 20-fold (considered a GoF effect), and p.(Met617Thr)
26 and p.(Phe655Ser), which increased EC_{50} by more than 20-fold (considered a LoF effect; Fig. 1B
27 and E, Supplementary Fig. S2, and Table S3).

28 AMPARs undergo profound desensitization in the continued presence of Glu, which is a
29 key property for EPSC shape and protects against excitotoxicity due to glutamatergic
30 hyperfunction⁶²⁻⁶⁴. For variants with a residual function, we assessed potential effects on
31 receptor desensitization by recording consecutive Glu currents in the absence (I_{GLU}) and presence

1 (I_{GLU+CTZ}) of CTZ block of desensitization (Fig. 2A). The WT GluA3 receptor showed
2 desensitized current amplitude of $2.8 \pm 0.4\%$, $n = 79$, of the non-desensitized current amplitude
3 (Fig. 2A-B; Supplementary Table S3); corresponding well with previously reported ratios for
4 homomeric GluA3⁶⁵⁻⁶⁷. Eight variants displayed significant increases in the desensitized current
5 as illustrated for a representative variant (p.(Ala654Val)) in Fig. 2A. The variants p.(Arg631Ser),
6 p.(Ala654Pro), p.(Ala654Val), and p.(Ala654Thr) showed the most profound effects, with near
7 identical current amplitudes under desensitizing and non-desensitizing conditions (Fig. 2A-B;
8 Supplementary Table S3), which indicate that the variants decrease or fully block receptor
9 desensitization, which is a GoF effect for AMPAR signalling. In contrast, seven variants
10 (p.(Ser531Cys), p.(Leu774Ser), p.(Thr776Met), p.(Trp799Leu), p.(Gly803Ala), p.(Thr816Ile),
11 p.(Gly826Asp)) significantly decreased the desensitized current relative to the non-desensitized
12 current, indicating an increase in receptor desensitization, which is considered a LoF effect (Fig.
13 2B; Supplementary Table S3).

14 We screened for changes in the activation properties of GluA3, comparing the receptor
15 current evoked by application of the weak partial agonist kainic acid (KA) versus the current
16 evoked by Glu^{68,69} (Fig. 2C). When desensitization was blocked, the KA current (I_{KA+CTZ}) at WT
17 GluA3 was $21 \pm 0.1\%$, $n = 85$, of the Glu current (Fig. 2B; Supplementary Table S3). The results
18 from the screening showed an increased KA efficacy for 12 variants (p. (Ala615Val),
19 p.(Arg631Ser), p.(Ser647Phe), p.(Ala654Prol), p.(Ala654Val), p.(Ala654Thr), p.(Arg660Ser),
20 p.(Arg660Thr), p.(Ser663Pro), p.(Trp799Leu), p.(Gly803Glu), and p.(Gly803Ala) (Fig. 2C;
21 Supplementary Table S3). This effect indicates an increase in the ability of GluA3 to translate
22 agonist binding to channel opening and is to be considered a GoF effect for overall receptor
23 function. In contrast, six variants (p.(Met617Thr), p.(Ala653Thr), p.(Phe655Ser), p.(Ile665Thr),
24 p.(Lys701Glu), and p.(Gly826Asp)) displayed decreased KA efficacy, and, therefore, reduced
25 ability to activate, which is a LoF effect for overall receptor function (Fig. 2B-C; Supplementary
26 Table S3). Notably, the KA/Glu current ratio has previously been electrophysiologically
27 characterized for homomeric GluA3 with the p.(Ala653Thr) variant with similar results²⁹.

28 Lastly, we screened for constitutive receptor activity, e.g., channel opening in the absence
29 of Glu, using 1-naphthyl acetyl spermine (NASPM), a selective open-channel blocker for
30 GluA2-lacking calcium-permeable AMPARs^{70,71}. Applying 1 μ M NASPM produced near-
31 complete inhibition of the Glu-evoked current for WT GluA3 and most variants (Fig. 2C-D;

1 Supplementary Table S3). However, for two variants (p.(Arg631Ser) and p.(Ala654Pro)),
2 NASPM application inhibited the membrane current below the level observed in the absence of
3 Glu (Fig. 2C), indicating constitutive channel activity. This effect was most profound for the
4 variant p.(Ala654Pro) (Fig. 2D; Supplementary Table S3). Specifically, in the absence of an
5 agonist and at a holding potential of -40 mV, XOs expressing the p.(Ala654Pro) variant
6 displayed approximately 10-fold increased membrane current (564 ± 123 nA; $n = 21$) compared
7 to XOs expressing the WT (receptor 61 ± 32 nA; $n = 20$). Also, the elevated membrane current
8 for p.(Ala654Pro) increased relatively little upon Glu application in the presence of block of
9 desensitization ($I_{\text{GLU}+\text{CTZ}} = 89 \pm 20$ nA; $n = 18$) compared to the membrane current in WT
10 expressing ($I_{\text{GLU}+\text{CTZ}} = 4230 \pm 490$ nA; $n = 140$), but decreased by more than 300% upon
11 NASPM application (Fig. 2D; Supplementary Table S3). Three variants (p.(Ala615Val),
12 p.(Met617Thr), and p.(Gly826Asp) showed decreased inhibition by NASPM. These variants
13 change residues located close to the NASPM binding site in the channel, and the decreased
14 inhibition by NASPM likely reflects a direct effect on the binding affinity of NASPM⁷².

15 The TEVC functional characterizations of the 43 missense *GRIA3* variants showed that
16 70% (30/43) changed one or more of the evaluated receptor parameters. As summarized in Fig.
17 2E, 18 of the missense variants showed a pattern of functional effects that point to an overall LoF
18 effect on receptor signalling function, including decreased or complete loss of desensitized and
19 non-desensitized current response to Glu (no or decreased I_{GLU} or $I_{\text{GLU}+\text{CTZ}}$, respectively),
20 reduced agonist sensitivity (increased EC_{50}), reduced activation ability (decreased $I_{\text{KA}}/I_{\text{GLU}}$ ratio),
21 or increased desensitization (decreased $I_{\text{GLU}}/I_{\text{GLU}+\text{CTZ}}$ ratio). In contrast, 12 variants showed effect
22 patterns that suggest an overall GoF effect; *e.g.*, increased current amplitudes, agonist sensitivity,
23 activation, including constitutive activity, and significantly reduced or completely blocked
24 desensitization (Fig. 2F). Two variants (p.(Trp799Leu) and p.(Ser531Cys)) showed a mixed
25 pattern of both GoF and LoF effects. Specifically, these variants showed no (p.(Ser531Cys)) or
26 greatly reduced (p.(Trp799Leu)) desensitized current, but WT-like current amplitude upon block
27 of desensitization (Fig. 1B-C, Supplementary Table S2 and S3). These results suggest a LoF
28 functional phenotype due to increased desensitization. On the other hand, both variants decreased
29 Glu EC_{50} dramatically (Fig. 1E; measured in the presence of CTZ), which is a GoF effect, and
30 for p.(Trp799Leu) also increased the KA efficacy, indicating increased ability to be activated
31 (Fig. 1B, Supplementary Table S3). However, we classified both variants to have an overall LoF

1 effect based on the reduced Glu current without blocked desensitization. Lastly, 13 variants did
2 not show significant changes in any of the evaluated functional parameters (Fig. 2G) and,
3 therefore, appeared neutral for the core ligand-gated channel function and were not investigated
4 further. However, we cannot rule out that these variants may affect other aspects of GluA3-
5 containing receptors beyond the functions studied here, such as receptor trafficking, regulation,
6 and interactions with synaptic proteins important for native AMPARs.

7 The domain distribution of the GoF, LoF, and functionally neutral variants shows that
8 GoF and LoF variants exclusively affect residues in the ABD, TMD, and ABD-TMD linkers,
9 whereas most neutral variants affect residues in the NTD and CTD (Fig. 2E-G). Overall, the
10 positions in the GluA3 sequence that are affected by LoF and GoF variants fit well with analysis
11 of missense tolerance ratio⁷³ (MTR) (Fig. 2H), as 87% (27/31) of the variants with functional
12 LoF or GoF affect residues in segments that appear highly intolerant to missense variation (Fig.
13 2H), whereas 69% (9/13) of the functionally neutral variants affect positions with no unusual
14 sensitivity to missense variation. This observation suggests that MTR analysis is a highly
15 effective predictor of potential pathogenicity of missense variants for *GRIA3*. In comparison, the
16 accuracy of the *in silico* prediction tools SIFT and PolyPhen in predicting the LoF/GoF variants
17 as pathogenic was 72% and 74%, respectively (Supplementary Table S1).

18

19 ***GRIA3* variant effects are dominant in heteromeric AMPA** 20 **receptors**

21 GluA3 subunits are thought to preferentially assemble with GluA2 subunits into heteromeric
22 GluA2/3 receptors in the brain, although triheteromeric GluA1/2/3 receptors have also recently
23 been shown⁷⁴⁻⁷⁷. Thus, native GluA3-containing AMPARs in affected patients will have two
24 subunits containing the variant. To assess whether variant effects were also present in
25 heteromeric GluA2/A3 receptors, we expressed the LoF or GoF variants together with WT
26 GluA2 and determined desensitized and non-desensitized current amplitudes, the degree of
27 desensitization, and the KA/GLU response ratio (Fig. 3A-C; Supplementary Table S4). For each
28 variant expressed with GluA2, the current-voltage (IV) relationship was determined, as this
29 provides a measure for formation of heteromeric GluA2/A3 receptors (Fig. 3E). Specifically,

1 incorporation of GluA2 subunits shifts the IV curve from inwardly-rectifying to linear (as
2 illustrated for WT and selected variants in Fig. 3E). All functional variants exhibited linear IV
3 relationships when expressed with GluA2, which shows that the variants retain their ability of
4 GluA3 to form heteromeric GluA2/A3 receptors. As summarized in Fig. 3D, the results showed
5 that GoF effects observed in homomeric GluA3 were highly penetrant to heteromeric GluA2/A3.
6 Specifically, significant changes for the affected parameters were also observed in GluA2/A3
7 receptors for all variants exhibiting one or more GoF effects. Similarly, for variants that induced
8 a LoF phenotype for homomeric GluA3, LoF effects were also observed in the heteromeric
9 receptor background. Notably, among the variants that completely abolished the Glu response in
10 homomeric GluA3 (p.(Gly492Ser), p.(Gly630Arg), p.(Met706Thr), p.(Gly721Arg),
11 p.(Glu787Lys), p.(Glu787Gly), and p.(Gly833Arg)), currents could be measured for all when
12 expressed as heteromers with GluA2, although with profoundly lower current amplitudes than
13 WT GluA2/A3 (Fig. 3D, Supplementary Table S2). The only exception was the p.(Gly721Arg)
14 variant, which showed a current amplitude similar to WT in heteromeric GluA2/A3 receptors
15 (Supplementary Table S2). For all of these variants, a linear IV relationship similar to WT
16 GluA2/3 was observed (Supplementary Fig. S3), confirming the presence of the GluA2 subunit
17 in the heteromeric receptor complex.

18 In summary, the characterization of the effects of the 43 *GRIA3* missense variants
19 revealed 31 (72%) to alter electrophysiological functions in both homomeric GluA3 and
20 heteromeric GluA2/3 receptors, strongly indicating these variants as pathogenic.

21

22 **Kinetic characterization and classification of the pathogenic** 23 **variants**

24 Based on the TEVC evaluations, we next aimed to collect detailed phenotypic and genetic
25 information from patients carrying the 31 *GRIA3* variants associated with significant LoF or GoF
26 effects on receptor function and, therefore, are strongly indicated as a monogenetic cause of
27 NDD. For 17 of these variants, we obtained detailed clinical information from 25 NDD patients,
28 resulting in a cohort of 14 males (patients M1-M14) and 11 females (patients F1-F11). The
29 genetic and phenotypic details of the patient cohort are described in the Supplementary results

1 and Supplementary Table S7. To further characterize how the 17 cohort variants perturb the
2 receptor functional phenotype, we utilized fast-application patch-clamp electrophysiology, which
3 can model the synaptic Glu pulses that evoke EPSCs on a millisecond timescale and can
4 accurately identify changes in receptor deactivation and desensitization rates that are particularly
5 important for shaping AMPAR synaptic signals. Specifically, the cohort variants were expressed
6 in HEK293 cells as homomeric GluA3 and heteromeric GluA2/A3 receptors. Current responses
7 to pulses of 10 mM Glu were recorded (*Materials & Methods*) (see Fig. 4A for an illustration of
8 the recording protocol and representative current traces), except for variants p.(Ala653Thr),
9 p.(Gly630Arg), and p.(Arg660Thr), which have previously been characterized with fast-
10 application patch-clamp electrophysiology in both homomeric GluA3 and heteromeric
11 GluA2/A3 receptors^{29,34,61}. AMPAR subunits occur in two isoforms, denoted flip and flop, which
12 result from alternative splicing of the two mutually exclusive exons, 14 and 15, respectively, and
13 have important differences in receptor kinetics⁷⁸. This alternative flip/flop splicing affects nine
14 amino acid positions in a 38 amino acid segment close to the ABD-M4 linker. The
15 p.(Glu787Gly) (patient M7), p.(Glu787Lys) (patient M8-9, F11), and p.(Trp799Leu) (patient F9)
16 variants originate in exon 14 and specifically affect the flop isoform. Therefore, these variants
17 were characterized in the flop isoform of GluA3 (GluA3_o). The remaining variants are located
18 outside the flip/flop segment and were characterized in the flip isoform (GluA3_i), which
19 predominates before birth and continues to be expressed in the adult brain⁷⁹.

20 The results showed a complete or very severe LoF effect on the current response to fast
21 Glu applications for the variants p.(Gly492Ser) (patient M2), p.(Phe655Ser) (patient M10),
22 p.(Ile665Thr) (patient F10), and p.(Glu787Gly) (patient M7) (Fig. 4A). In addition, the variants
23 p.(Gly630Arg) (patients M3-6) and p.(Glu787Lys) (patient M8-9, F11) that previously have been
24 characterized with identical recording protocols, also have a complete LoF phenotype⁶¹.
25 Moreover, expressed together with WT GluA2, all these variants also abolished the current
26 response in heteromeric GluA2/A3 receptors, except for p.(Ile665Thr) (patient F10), which
27 showed a robust and desensitizing current response (Fig. 4A). To test whether the complete or
28 severe LoF effect was due to the variants perturbing expression and folding of the GluA3 subunit
29 protein, or subunit ability to assemble into receptors that traffic to the membrane, we expressed
30 β -lac-tagged WT and variant GluA3 constructs in HEK293 cells (Supplementary methods).
31 Analysis of the conversion rates of the β -lac substrate nitrocefin from transfected HEK293 cells

1 revealed no significant difference in cell-surface expression between WT and variant receptors
2 (Supplementary Fig. S4). Thus, we conclude that the LoF effect that these variants have on Glu
3 current is due to disruption of the core ligand-gated channel function of the receptor. The
4 p.(Trp799Leu) variant showed measurable currents but with greatly reduced peak amplitude. In
5 homomeric GluA3, due to the reduced currents we were only able to reliably determine the
6 desensitization rate of the p.(Trp799Leu) variant in a single experiment, which showed 3-fold
7 increased rate of desensitization ($\tau_{\text{des}} = 0.57$ ms versus 1.58 ± 0.05 ms; $n = 15$ for WT GluA3_o)
8 and no measurable steady-state current (Fig. 4A-B; Supplementary table S5). These effects were
9 also observed in the heteromeric GluA2/A3 receptor (Fig. 4A-B; Supplementary table S5), where
10 slightly more robust currents allowed us to accurately determine the desensitization kinetics. and
11 suggest p.(Trp799Leu) is a severe LoF variant by greatly reducing charge transfer due to an
12 increased rate and extent of receptor desensitization. Notably, this is supported by the TEVC
13 characterizations that showed that the diminished Glu current for p.(Trp799Leu) could be fully
14 rescued by the pharmacological block of desensitization (Fig. 2 and 3).

15 The GoF variants p.(Ala654Val), p.(Ala654Thr), p.(Ala654Pro), p.(Ser663Pro),
16 p.(Lys701Glu), p.(Gly803Ala), and p.(Gly803Glu) all produced robust currents when expressed
17 as homomeric and heteromeric receptors (Fig. 4A). For these variants we determined the
18 desensitization rate (τ_{des}) and peak-to-steady-state current ratio (I_{ss}) from 500 ms glutamate
19 stimulations (Fig. 4B-C) and the deactivation rate (τ_{deact}) from 1 ms stimulations (Fig. 4D-E,
20 Supplementary table S5) (Materials and methods). As predicted from the TEVC results,
21 p.(Ala654Val) (patient F5), p.(Ala654Thr) (patient F7), and p.(Ala654Pro) (patient F6) displayed
22 greatly decreased desensitization. Specifically, whereas WT GluA3_i currents almost completely
23 decayed within milliseconds ($\tau_{\text{des}} = 5.3 \pm 0.3$ ms; $n = 12$) to a small fraction of the peak current
24 ($I_{\text{ss}} = 1.1 \pm 0.1\%$; $n = 16$), the p.(Ala654Pro) variant completely blocked ($I_{\text{ss}} = 100 \pm 0.0\%$, $n =$
25 4), and the p.(Ala654Thr) and p.(Ala654Val) variants greatly reduced the level of desensitization
26 ($I_{\text{ss}} = 82 \pm 3\%$, $n = 9$, and $61 \pm 2\%$, $n = 9$, respectively). In addition, the deactivation rates for
27 these variants were also slowed ($\tau_{\text{deact}} = 5\text{-}22$ ms; $n = 3\text{-}9$) compared to WT ($\tau_{\text{deact}} = 2.1 \pm 0.2$
28 ms; $n = 9$) for homomeric GluA3 receptors (Fig. D-E, Supplementary table S5). These effects
29 were maintained for the heteromeric GluA2/A3 receptor, where the p.(Ala654Pro) variant
30 completely blocked desensitization and slowed deactivation, and the p.(Ala654Val) and
31 p.(Ala654Thr) decreased desensitization and slowed deactivation, except for p.(Ala654Val),

1 which showed a deactivation rate not different from WT (Fig. B-C, Supplementary table S5).
2 Thus, the three variants affecting Ala654 can be classified as severe GoF due to profoundly
3 decreased desensitization and reduced deactivation rates. The variants p.(Ser663Pro) (patient F4)
4 and p.(Lys701Glu) (patient F3) displayed phenotypes quite similar to each other, which included
5 significantly increased I_{ss} levels, slowed desensitization rates, and modestly but significantly
6 slowed deactivation rates in both homomeric and heteromeric receptors (Fig. B-C,
7 Supplementary table S5). Lastly, the two variants affecting Gly803 (p.(Gly803Ala) and
8 p.(Gly803Glu)) showed normal I_{ss} levels but reduced desensitization and deactivation rates (Fig.
9 B-C, Supplementary Table S5). These changes, as a consequence of p.(Ser663Pro),
10 p.(Lys701Glu), p.(Gly803Ala), and p.(Gly803Glu) variants, are predicted to have a clear GoF
11 effect on the synaptic charge carried by GluA3-containing AMPARs, although to a less severe
12 extent than the variants affecting Ala654.

13

14 **Correlation of LoF and GoF receptor effects with patient clinical** 15 **phenotype**

16 We next compared patient clinical information with the receptor phenotypic information. As
17 summarized in Fig. 5A, we classified the variants based on the GoF and LoF effects identified in
18 the electrophysiological analyses as severe or mild. In addition, data from previously reported
19 evaluations of the p.(Ala653Thr)²⁹ and p.(Arg660Thr)³⁴ variants were included. For LoF
20 variants, the severe class includes seven variants in 11 patients (M1-M10 and -F10; Fig. 5A) that
21 completely abolish the current response to millisecond Glu stimulation, whereas the mild class
22 includes two variants from three patients (p.(Ala653Thr) in patients M11-12 and p.(Trp799Leu)
23 in patient F9), which show current response to fast Glu stimulation, but with greatly reduced
24 amplitude and profound changes in desensitization and deactivation kinetics that overall are
25 predicted to reduce synaptic charge transfer. For GoF variants, the mild class includes four
26 patients with variants p.(Gly803Ala) (patient M13) and p.(Gly803Glu) (patients M14 and F1-2),
27 which slow desensitization and deactivation rates significantly and increase Glu sensitivity, but
28 do not appear to change peak or desensitized current levels. The severe GoF class includes the
29 variants p.(Ala654Val), p.(Ala654Pro), and p.(Ala654Thr) (patients F5-F7, respectively)), in
30 addition to p.(Ser663Pro) (patient F4)), p.(Arg660Thr) (patient F8)), and p.(Lys701Glu) (patient

1 F3), which all significantly reduce desensitization and deactivation rates, increase Glu sensitivity
2 and increase steady-state current amplitudes in the TEVC experiments (Fig. 5A).

3 Several differences between the GoF and LoF patient classes (10 patients with GoF
4 variants and 15 patients with LoF variants) were identified (Table 1 and Fig. 5B). Importantly,
5 LoF and GoF variants are disease-causing in both sexes but affected males predominantly
6 (12/14) carry hemizygous LoF variants. In contrast, most affected females (8/11) carry
7 heterozygous GoF variants. Another striking difference includes the age of seizure onset in the
8 subgroup of patients with epileptic comorbidities, muscle tone (hypo- versus hypertonia), sleep
9 difficulties, and movement disorders, including hyperekplexia (Fig. 5B and Table 1).
10 Specifically, for the patients with epileptic comorbidities, the median age of seizure onset in
11 patients harboring a GoF was 1 month (range 1st day-12 months, $n = 5$), being significantly
12 earlier than in patients with LoF variants, being 16.5 months (range 12-36 months, $n = 6$, $P =$
13 0.004). We detected no significant differences between the GoF and LoF groups when
14 comparing seizure types ($P = 0.85$) and treatment response ($P = 1$). For body tone, most patients
15 harboring a LoF variant had congenital muscular hypotonia ($n = 10/15$), which was not reported
16 in any of the 10 patients with GoF variants ($P = 0.0004$). In contrast, congenital muscular
17 hypertonia was present in 8/10 patients with GoF variants, while it was only reported in 1/15
18 patients with LoF variants ($p = 0.0002$). Sleep disturbances were reported in 10/15 patients with
19 LoF variants, while they were only present in 2/10 patients with GoF variants ($p = 0.0018$).
20 Movement disorders of any kind were reported in 5/15 patients with LoF variants, while they
21 were present in 8/10 patients with a GoF variant ($p = 0.04$). In particular, an excessive startle
22 response to external stimuli, also known as hyperekplexia, was more prevalent in the group with
23 GoF variants ($n = 5$) compared to the group with LoF variants ($n = 1$) ($p = 0.003$). For
24 behavioural abnormalities, aggressive outbursts were more prevalent in the LoF cohort ($n = 6$)
25 compared to the GoF cohort ($n = 2$), although the difference was not significant ($p = 0.29$). There
26 were no significant differences in the other behavioural abnormalities reported in the GoF ($n = 6$)
27 compared to the LoF cohort ($n = 10$) ($p = 0.75$). Although all patients had ID, we found no
28 significant difference in severity between the GoF and LoF cohorts ($p = 0.26$). Specifically, ID
29 was reported to be borderline/mildly ($n = 1$), moderately ($n = 5$), severely ($n = 8$), or profoundly
30 ($n = 1$) affected in the LoF cohort, while moderately ($n = 4$), severely ($n = 3$) or profoundly ($n =$
31 3) affected in the GoF cohort.

1 In summary, the phenotypic assessment indicates that GoF variants are objectively
2 associated with more severe outcomes: patients were younger at the time of seizure onset,
3 hypertonic, and more often had movement disorders, including hyperekplexia. In contrast,
4 patients with LoF variants were older at seizure onset, hypotonic, and had sleep difficulties.
5

6 Discussion

7 Missense variants in *GRIA3* are by far the most prevalently reported *GRIA* genetic defects in
8 NDD patients. However, the extent to which the variants underlie NDDs is not clear, as few have
9 been studied in cellular or animal models to confirm them as pathogenic variations. The present
10 work systematically evaluates 44 rare *GRIA3* variants in NDD patients to establish whether these
11 have functional effects on GluA3-containing AMPARs. Focusing on effects on core ligand-gated
12 ion channel function, we find that 31 variants produced significant effects and were classified as
13 LoF or GoF concerning overall receptor signalling capability. We correlate the identified effects
14 on receptor function with the clinical features and find distinct GoF and LoF phenotypes. This
15 specific LoF-GoF difference in clinical phenotype is in line with several other central nervous
16 system (CNS) ion channel gene families, including the *GRIN* iGluR gene subfamily⁸⁰, where
17 studies applying detailed electrophysiological analysis of rare missense variant effects have
18 established both LoF and GoF effects as pathogenic, with each category often leading to
19 different disease phenotypes^{81–86}. In addition to the clinical importance of providing a diagnosis
20 and new disease understanding, identifying pathogenic variants as having LoF or GoF effects on
21 channel function is also of therapeutic relevance as it potentially guides pharmacological
22 intervention. For the iGluR gene families, this approach of systematic and detailed testing of
23 pathogenic variants from patient cohorts and their clinical and therapeutic relevance has been
24 successfully implemented for the NMDAR-encoding *GRIN* gene family, leading to a definition
25 of specific neurological conditions associated with types of variant effect and examples of
26 successful therapeutic intervention^{64,87,88}. In this paper, we extend the value of this approach to
27 the *GRIA* family. Moreover, our data advances the understanding of the role of abnormal
28 function of AMPARs in general and GluA3-containing subtypes in particular in NDD
29 syndromes. Firstly, as 71% of the evaluated variants altered GluA3-containing AMPAR
30 function, *GRIA3* can be firmly classified as a general disease gene in NDDs, and underscores the

1 importance of appropriate AMPAR signalling for CNS development, as also suggested in single
2 case or smaller cohort studies for *GRIA1*, *GRIA2*, and *GRIA3*^{22,29,30,32–34}. Secondly, our work
3 expands the spectrum and frequency of functional effects of pathogenic *GRIA3* variants by
4 identifying distinct types of LoF and GoF effects and providing clear genotype-phenotype
5 correlations that define two clinical phenotypes associated with predicted LoF and GoF effects:
6 LoF variants often lead to muscular hypotonia, hyporeflexia, a sleep disorder, aggressive
7 behaviour and later onset of seizures, whereas GoF variants are associated with muscular
8 hypertonia, hyperreflexia, startle-induced non-epileptic myoclonia and earlier onset of seizures.

9 Although the GoF variants appear to be associated with more severe outcomes, such as
10 earlier seizure onset and a higher prevalence of movement disorders, including hyperekplexia, all
11 patients present with overall severe NDD phenotypes independent of the type of LoF or GoF
12 effect of the *GRIA3* variants. This observation suggests that even quantitatively small alterations
13 from WT AMPAR function lead to severe outcomes, which likely reflects the crucial role of
14 AMPARs in the ability of excitatory synapses to detect transmission events rapidly. As
15 excitatory synaptic currents can occur at rates of up to several hundred Hz, AMPARs have likely
16 evolved with precisely balanced Glu sensitivity and extremely fast rates of activation,
17 desensitization, and deactivation within a very narrow range. Thus, although some LoF and all
18 GoF effects do not prevent the contribution of GluA3-containing AMPARs to synaptic
19 transmission, they are likely to perturb the fidelity of neuronal activation. It is also noteworthy
20 that patient M1, who is hemizygous for the protein-truncating complete LoF variant
21 p.(Gln371Argfs*6), appears to have the least severe symptoms compared to those with missense
22 LoF variants, in particular in respect to the severity of ID (Table 1). This finding suggests that
23 the complete loss of GluA3-containing receptors from synaptic AMPAR populations is better
24 tolerated than the existence of GluA3-containing receptors with perturbed function. Interestingly,
25 similar findings have been reported for γ -Aminobutyric acid A (GABA_A) receptors⁸⁹. Further
26 detailed evaluation of more pathogenic *GRIA3* variants is warranted to explore how clinical
27 severity correlates to variant effects on receptor function and will likely require establishing
28 models for studying the variant impact on synaptic transmission and animal behavioural
29 phenotypes.

30 The current data set also provides insight into emerging associations among sex and
31 inheritance, which often is complicated for morbid genes on the X-chromosome, as it is not

1 always possible to predict the phenotypical effect in heterozygous females. Our data set
2 establishes that LoF and GoF variants as disease-causing in both sexes, but that affected males
3 more often (12/14) carry hemizygous LoF variants, whereas most affected females (8/11) carry
4 heterozygous GoF variants. Although our data do not support a strict model, the prevalence of *de*
5 *novo* GoF in females is consistent with the general understanding that LoF variants are likely to
6 be less harmful in heterozygous females⁹⁰. However, evaluation of further *GRIA3* variants in
7 males and females is needed to explore *i*) the prevalence of GoF variants in females and LoF
8 variants in males and *ii*) to describe if males with GoF variants are equally or more severely
9 affected than females with similar variants.

10 Next-generation sequencing has become routine in hospitals, and the number of NDD
11 patients with a genetic etiology is increasing^{91,92}. As a result, the number of new *GRIA* variants
12 needing a functional assessment is expected to rise. In addition to confirming pathogenicity,
13 functional testing provides knowledge crucial for treatment, as choosing the right drug (effective
14 and not exacerbating the existing symptoms) depends on establishing LoF or GoF status. In this
15 respect, establishing the impact of new variants on AMPAR function via electrophysiological
16 evaluation may become a critical bottleneck in individual cases, highlighting a need to develop
17 approaches for the theoretical prediction of variant pathogenicity and LoF/GoF effects. Notably,
18 recent large-scale bioinformatical efforts for exploring new approaches for prediction of
19 pathogenicity of variants in genes encoding voltage- and ligand-gated ion channel subunits have
20 suggested that clinical decision support algorithms that predict LoF/GoF status based on location
21 in protein structure may become feasible⁹³. Specifically, it was shown that certain positional
22 measures of the variant in the structures of voltage-gated sodium channels and NMDA receptors
23 could be correlated to functional effect and clinical phenotype⁹³. For similar purpose in GluA3-
24 containing AMPA receptors, we note that when considering the variant distribution throughout
25 the GluA3 structure, it is observed that functionally neutral variants are enriched in the NTD,
26 whereas LoF or GoF variants localize in the ABD, linker, and TMD segments (Fig. 1 and 2).
27 However, we find several examples of close clustering of neutral, LoF, and GoF variants in these
28 domains, which suggests that the clinical interpretation of missense variants in *GRIA3* as well as
29 GoF/LoF classifications based on general localization measures in the receptor structure should
30 be cautious.

1 For several pathogenic *GRIA3* variants, our analysis allows us to pinpoint the mechanistic
2 cause of the overall LoF or GoF effect. This knowledge provides an opportunity for exploring
3 clinically relevant AMPAR drugs for the pharmacological rescue of receptor function among
4 different classes of variant phenotypes. Notably, for variants with LoF effects on AMPAR
5 kinetics, positive allosteric modulators (PAMs) exist, in particular of the *ampakine* class, that can
6 modulate AMPAR current amplitude and waveform via selective effects on receptor kinetics⁹⁴.
7 Although no AMPAR PAM currently is FDA/EMA approved, several have passed Phase I/II
8 clinical trials, such as CX516⁹⁵, CX717 (Fasoracetam)⁹⁶, Org 24448 (Aniracetam)⁹⁷, and
9 CX1739⁹⁸, including early proof-of-concept trials in patients with cognitive impairments⁹⁹, and
10 are subjects for ongoing clinical development. Similarly, for variants with GoF effects (e.g.,
11 increased activation or decreased desensitization), negative allosteric modulators (NAMs) can be
12 explored, including perampanel, which inhibits activation and accelerates desensitization¹⁰⁰.
13 Importantly, perampanel is approved for chronic treatment of several types of epilepsy¹⁰¹, and
14 therefore, directly available as a potential precision medicine for patients with GoF AMPAR
15 mutations, as recently has been demonstrated for GoF variants in other *GRIA* genes¹⁰².

16 The present study represents the largest functional evaluation of missense variants in any
17 *GRIA* gene. Together with previous work on *GRIA1*, *GRIA2*, and *GRIA3*, the volume of
18 validated pathogenic *GRIA* variants has now reached a critical point that firmly establishes *GRIA*
19 genetic defects as the cause of an emerging neurological disease, recently referred to as *GRIA*
20 disorder¹⁰². However, further understanding of *GRIA* disorder disease mechanisms and
21 potentially devising standard rescue pharmacological strategies is complicated by the diversity of
22 the native AMPAR subtypes that a pathogenic variant can affect. Notably, we focused our
23 functional work on the homomeric GluA3 and the heteromeric GluA2/A3 subtypes in two
24 heterologous expression models, which lack the postsynaptic proteins that interact with native
25 AMPARs and contribute to their synaptic functions. Most native AMPARs assemble with
26 different transmembrane AMPA receptor regulatory proteins (TARPs), which act as auxiliary
27 subunits and have distinct effects on receptor function, including modulation of receptor gating
28 and desensitization properties^{64,103}. These effects may have significant implications for the
29 variant effect on synaptic transmission, and further work is required to provide insights into how
30 *GRIA* variants affect AMPAR function involving auxiliary subunits. Also, the absence of a
31 neuronal environment presents a caveat to the classification of variants that do not display

1 functional effects, as functionally neutral variants may have detrimental effects on other aspects
2 of AMPAR cellular biology, such as receptor incorporation and positioning at synapses and
3 regulation during synaptic plasticity mechanisms. Specifically, our evaluation did not reveal
4 effects on the core function of GluA3-containing AMPARs for 13 variants when evaluated in
5 recombinant GluA3 receptors (Fig. 1). Recent progress in mapping the AMPAR interactome in
6 the brain shows that native AMPARs during the receptor lifetime interact with more than 40
7 intracellular, extracellular, or membrane-embedded proteins, which are important for proper
8 receptor biogenesis, postsynaptic positioning, and function¹⁰⁴. We cannot rule out that apparently
9 neutral variants may indeed influence expression and function of native GluA3-containing
10 AMPARs by interfering with the ability of the GluA3 subunit to interact with synaptic
11 constituents, and confident classification of *GRIA3* variants as neutral is thus not possible in
12 current practise. Therefore, studies beyond establishing the functional defects of *GRIA* variants
13 are needed to describe effects in a synaptic context. Importantly, the impact of LoF/GoF variants
14 on the AMPAR-component of EPSC currents should be determined and correlated with the
15 effects on kinetic parameters obtained from heterologous expression systems. This will improve
16 the framework of predicting synaptic effects for variants based on functional evaluations in
17 reduced systems such as XOs or HEK293 cells.

18 We have characterized the consequences of 44 *GRIA3* variants identified in NDD patients
19 on GluA3-containing receptor function. Although the spectrum of variant effects on AMPAR
20 signalling mechanisms that underlie the phenotype of each patient is likely to be complex, our
21 analysis shows two significant genotype-phenotype correlations that correspond to predicted
22 GoF or LoF effects on the signalling function of GluA3-containing AMPARs.

23

24 **Data availability**

25 The authors confirm that the data supporting the findings of this study are available in the main
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27

28

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24

25 **Competing interests**

26 The authors report no competing interests.

27

1 **Supplementary material**

2 Supplementary material is available at *Brain* online.

3

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16 **Figure legends**

17 **Figure 1 Location of *GRIA3* variants in the GluA3 receptor and effect on glutamate-gated**
18 **channel function.** (A) Structural model of homomeric GluA3 receptor encoded by the *GRIA3*
19 gene built from structures of the GluA2 receptor (*Supplementary materials & methods*). The top
20 left panel shows a surface representation of the tetrameric receptor complex with the four
21 identical subunits in shades of gray and blue. The bottom panel shows a cartoon representation of
22 a single GluA3 subunit with the N-terminal domain (NTD) in light blue, the agonist-binding
23 domain (ABD) in blue, and the transmembrane domain (TMD) in magenta. Zoomed views of the
24 NTD, ABD, and TMD shows the position of genetic variants caused by *GRIA3* missense variants
25 highlighted by different colors according to the apparent effect on homomeric GluA3 function as
26 neutral (*gray*), LoF (*red*), and GoF (*green*). Orange circle indicate the position of the Glu binding
27 site in the LBD. (B) Summary of desensitized (Glu) and non-desensitized (Glu+CTZ) current
28 amplitudes and Glu EC50 for homomeric GluA3 receptors containing genetic variants encoded

1 by the *GRIA3* variants evaluated in this study. Values, number of measurements, and statistical
2 parameters are given in Tables S2 and S3. Individual data points are color-coded according to the
3 effect on currents or EC50 (LoF effect; *red*) or increase (GoF effect; *green*). For the EC50 panel,
4 data points shown as squares represent EC50 values determined with CTZ. (C) Representative
5 current responses from TEVC recordings of XO ($V_{\text{HOLD}} -40$ mV) expressing WT or *GRIA3*
6 variant-containing GluA3 receptors in response to Glu application ($300 \mu\text{M}$, *black bar*) in the
7 presence of CTZ ($100 \mu\text{M}$) to block desensitization. (D) Representative current recordings from
8 TEVC Glu concentration-response experiments of WT GluA3 and selected variants
9 exemplifying neutral (p.(Ala615Val)), increasing (p.(Ala654Val)), or decreasing
10 (p.(Thr776Met)) effect on receptor responsiveness to Glu. (E) Composite concentration-response
11 curves for WT and selected *GRIA3* variant-containing GluA3 receptors. Data points represent the
12 mean of 6 to 12 oocytes. Error bars are the SEM and are shown when larger than the symbol
13 size. The current responses are normalized to the maximal response evoked by Glu. In all panels,
14 variants are labelled with single-letter amino acid codes.

15

16 **Figure 2 Variant effects on receptor desensitization and activation properties.** (A)
17 Representative currents evoked by sequential 10-20 s applications of Glu (1 mM , *black bar*)
18 alone and in the presence of CTZ ($100 \mu\text{M}$, *gray bar*) from oocytes expressing WT GluA3 and
19 GluA3 carrying selected *GRIA3* missense variants. The p.(Pro302Ser) variant shows no change
20 in the size of the desensitized current relative to the non-desensitized Glu current compared to
21 WT, the p.(Ala654Val) variant shows increased desensitized current, and the p.(Thr816Ile)
22 variant show decreased desensitized current. (B) Representative currents evoked by sequential
23 10-20 s applications of Glu (1 mM , *black bar*) and KA ($300 \mu\text{M}$; *blue bars*) in the presence of
24 CTZ ($100 \mu\text{M}$, *gray bar*) from oocytes expressing WT GluA3 and GluA3 containing selected
25 variants exemplifying different types of variant effects on KA/GLU response ratio. For WT
26 GluA3 and the p.(Pro302Ser) variant, the KA-evoked current has an amplitude of 16% of the
27 Glu current amplitude. In contrast, the p.(Ala654Val) variant has a relative KA current of 41%,
28 indicating an increase in activation properties, and p.(Ala653Thr) variant has decreased relative
29 KA response amplitude of 3.5%, indicating decreased activation properties. The holding
30 potential was -40 mV in all shown recordings. (C) Representative currents illustrating NASPM
31 ($1 \mu\text{M}$, *red bar*) inhibition of Glu evoked currents for WT GluA3 and GluA3 containing the

1 variants p.(Arg631Ser) and p.(Ala654Pro) **(D)** Summary of the ratio of desensitized and non-
2 desensitized current amplitude ($I_{\text{Glu}}/I_{\text{Glu+CTZ}}$), non-desensitized Glu and KA ($I_{\text{KA+CTZ}}/I_{\text{Glu+CTZ}}$)
3 current amplitudes and NASPM inhibition of Glu-evoked current for homomeric GluA3
4 receptors containing genetic variants encoded by the *GRIA3* variants evaluated in this study.
5 Values, number of measurements, and statistical parameters are given in Table S2. Individual
6 data points are color-coded according to the effect on currents or EC_{50} (LoF effect; *red*) or
7 increase (GoF effect; *green*). **(E-G)** Summary of phenotype and domain location of variants with
8 overall GoF (E), LoF (F), and neutral (G) effect on homomeric GluA3 receptor function.
9 Symbols indicate: ▼; decrease, ▲; increase, ●; no change, -; not determined. Color coding
10 indicates a predicted LoF (*red*) or GoF (*green*) effect of change on overall receptor function. **(H)**
11 Missense tolerance ratio (MTR) of *GRIA3* variants analyzed with a 31 amino acid window
12 calculated using the MTR-viewer online tool (<https://biosig.lab.uq.edu.au/mtr-viewer/>)¹⁰⁵. A line
13 graph displays the MTR distribution for *GRIA3* (gene transcript NM_000828) with regions in
14 orange indicating observed variation differs significantly from neutrality. Dashed lines on the
15 plot denote gene-specific MTRs: green = 5th percentile, purple = 25th percentile and black =
16 50th percentile. Above the MTR distribution is shown the domain structure of the GluA3
17 subunit. Variant positions are shown as circles on the MTR line graph and colored according to
18 functional effect as: neutral (*gray*), GoF (*green*), and LoF (*red*). Orange line segments indicate
19 regions where the observed variation differs significantly from neutrality. In all panels, variants
20 are labelled with single-letter amino acid codes.

21
22 **Figure 3 Variant effects in heteromeric GluA2/A3 receptors.** **(A)** Representative currents
23 evoked by sequential 10-20 s applications of Glu (1 mM, *black bar*) alone and in the presence of
24 CTZ (100 μM , *gray bar*) from oocytes expressing WT GluA2 and WT GluA3 and WT GluA2
25 with GluA3 carrying selected *GRIA3* missense variants illustrating increased (p.(Ala654Val),
26 *middle trace*) and decreased (p.(Leu774Ser); *lower trace*) desensitized current. **(B)**
27 Representative currents evoked by sequential 10-20 s applications of Glu (1 mM, *black bar*) and
28 KA (300 μM ; *blue bars*) the presence of CTZ (100 μM , *gray bar*) from oocytes expressing WT
29 GluA2 and WT GluA3 and WT GluA2 with GluA3 carrying selected *GRIA3* missense variants
30 illustrating increased (p.(Ala615Val), *middle trace*) and decreased (p.(Ala653Thr); *lower trace*)
31 current response to KA relative to Glu. **(C)** Representative current recordings from TEVC Glu

1 concentration-response experiments of WT and selected variants in heteromeric GluA2/A3
2 receptors with corresponding fitted dose-response curves for homomeric (A3) and heteromeric
3 (A2/A3) receptors. The p.(Trp799Leu) exemplifies a variant changing the EC₅₀ in both
4 homomeric and heteromeric receptors, whereas p.(Thr776Met) exemplifies a variant affecting
5 only homomeric receptors. Color code of curves indicate effect on EC₅₀: Decrease (*green*),
6 increase (*red*), or neutral (*gray*). **(D)** Overview and summary of the effects on heteromeric
7 GluA2/A3 receptor parameters (*squares*) of *GRIA3* variants with GoF (*green*) and LoF (*red*)
8 effects. Data points represent the mean and 95% CI values (see Supplementary Tables S2 and
9 S3). **(E)** IV relationships of Glu-evoked currents from oocytes expressing homomeric WT and
10 variant-containing GluA3 alone (*white circles*) and with WT GluA2R (*black circles*). The
11 current amplitude at the different holding potentials is normalized to the current at -40 mV. Data
12 points represent the mean from 6 to 10 oocytes. Error bars indicate the SEM and are shown when
13 larger than the symbol size. In all panels, variants are labelled with single-letter amino acid
14 codes.

15
16 **Figure 4 Characterization of variant effect on fast receptor kinetics.** **(A)** Representative
17 whole-cell currents evoked by a 500 ms application of Glu (10 mM, *black bar*) from homomeric
18 GluA3 (*left*) and heteromeric GluA2/A3 receptors carrying the indicated *GRIA3* variants
19 subunits expressed in HEK293 cells. The holding potential was -70 mV in all recordings. Note
20 that scale bars for current amplitude differ between recordings. **(B)** The time constant (τ_{des}) and
21 level (I_{ss}) of current desensitization determined from the fitting of the current decay (*insert*)
22 during 500 ms applications of Glu (10 mM, *black bars*) fitted to two-exponential decay functions
23 weighted by proportional contributions for WT and variant homomeric GluA3 (*left*) and
24 heteromeric GluA2/A3 (*right*) receptors. **(C)** Summary of the τ_{des} and I_{ss} values. Bars represent
25 the mean with SEM error. Values not determined due to low or no current are labelled *nd*. **(D)**
26 Deactivation rates (τ_{deact}) determined from the fitting of the current decay (*insert*) following 1 ms
27 application of Glu (10 mM, *black bars*) fitted to a mono-exponential decay function (*inserts*) for
28 WT and variant homomeric GluA3 (*left*) and heteromeric GluA2/A3 (*right*) receptors. **(E)**
29 Summary of τ_{deact} values. Bars represent the mean with SEM error. Values not determined due to
30 low or no current are labelled *nd*. **(F)** Summary of effects of patient variants on current kinetics
31 and location in GluA3 subunit. Variants with LoF effects are shown in red and GoF in green. ▼;

1 decrease, ▲; increase, ●; no change, -; not determined. In all panels, variants are labelled with
 2 single-letter amino acid codes.

3

4 **Figure 5 Variant classification and phenotype correlations for patient M1-M12 and F1-F10.**

5 (A) Schematic overview of the classification of receptor phenotype for patients M1-M13 and F1-
 6 F11 into severe and mild GoF (*green*) and LoF (*red*) categories based on variant effect patterns
 7 on GluA3-containing receptor function together with an overview of the number of patients and
 8 prevalence of key patient symptoms for each category. (B) Summary of key and supporting
 9 features for the clinical phenotypes associated with LoF and GoF variants. The diagram
 10 summarizes several clinical findings that can help predict if a *GRIA3* variant leads to loss-of-
 11 function (LoF) and gain-of-function (GoF). GoF variants manifest with seizures occurring before
 12 the first year of life (with a median age of 1 month) and are characterized by supporting features
 13 such as hypertonia, hyperekplexia/excessive startle reflex, and the absence of sleep disturbances.
 14 LoF variants manifest with key features such as seizure onset after the first year of life (with a
 15 median age of 16 months) and supporting features including hypotonia, sleep disturbances, and
 16 the absence of hyperekplexia/excessive startle reflex. If a patient's phenotypical presentation
 17 displays a combination of these features, functional testing of the variant is required to determine
 18 whether a *GRIA3* variant displays LoF or GoF characteristics. ^{a-d} *P* values for comparing
 19 proportions of clinical indicators between the LoF or GoF patients: ^a Age of seizure onset < 12
 20 months versus age of seizure onset > 12 months; *P* = 0.004, ^b hypertonia versus hypotonia; *P* =
 21 0.0004, ^c hyperekplexia/startle versus no hyperekplexia/startle; *P* = 0.003, ^d sleep disturbance
 22 versus no sleep disturbance; *P* = 0.018.

23

24 **Table 1 Comparison of clinical features reported in patients with loss-of-function *GRIA3* variants compared to features**
 25 **reported in those with gain-of-function *GRIA3* variants**

Feature	Loss-of-function	Gain-of-function
Number of patients	15	10
Male	12/15 (80%)	2/10 (20%)
Female	3/15 (20%)	8/10 (80%)
Epilepsy diagnosis	5/15 (33%)	6/10 (60%)
Median age at onset of seizures	16 months (range 9 mo to 3 yrs)	1 month (range 1 st day to 27 yrs)
Treatment resistant seizures	3/5 (60%)	4/6 (66%)
Developmental delay or cognitive impairment	15/15 (100%)	10/10 (100%)

	Degree: borderline = 1 mild-moderate = 1 moderate = 4 severe = 7 severe-profound = 1 profound = 1	Degree: moderate = 4 severe = 2 severe-profound = 1 profound = 3
Muscular hypotonia	12/15 (80%)	0/10 (0%)
Muscular hypertonia	2/15 (13%)	9/10 (90%)
Hyporeflexia	10/15 (66%)	0/10 (0%)
Hyperreflexes	1/15 (6%)	7/10 (70%)
Spasticity	1/15 (6%)	4/10 (40%)
Movement disorder or any kind	7/15 (46%)	8/10 (80%)
Hyperexplexia or stimulus sensitive non-epilepticus myoclonia	2/15 (13%)	6/10 (60%)
Sleep disorder	10/15 (66%)	3/10 (33%)
Behavioral issues of any kind	10/15 (66%)	5/10 (50%)
Aggressive outburst or self-damaging behavior	6/15 (40%)	2/10 (20%)
Magnetic resonance imaging (MRI) performed	9/15 (60%)	9/10 (90%)
Abnormal MRI	2/9 (22%)	2/9 (22%)

1 The table summarizes key clinical features in the loss-of-function and gain-of-function patient groups. Detailed clinical information for individual
2 patients is provided in Supplementary Information and Table S7.

ACCEPTED MANUSCRIPT

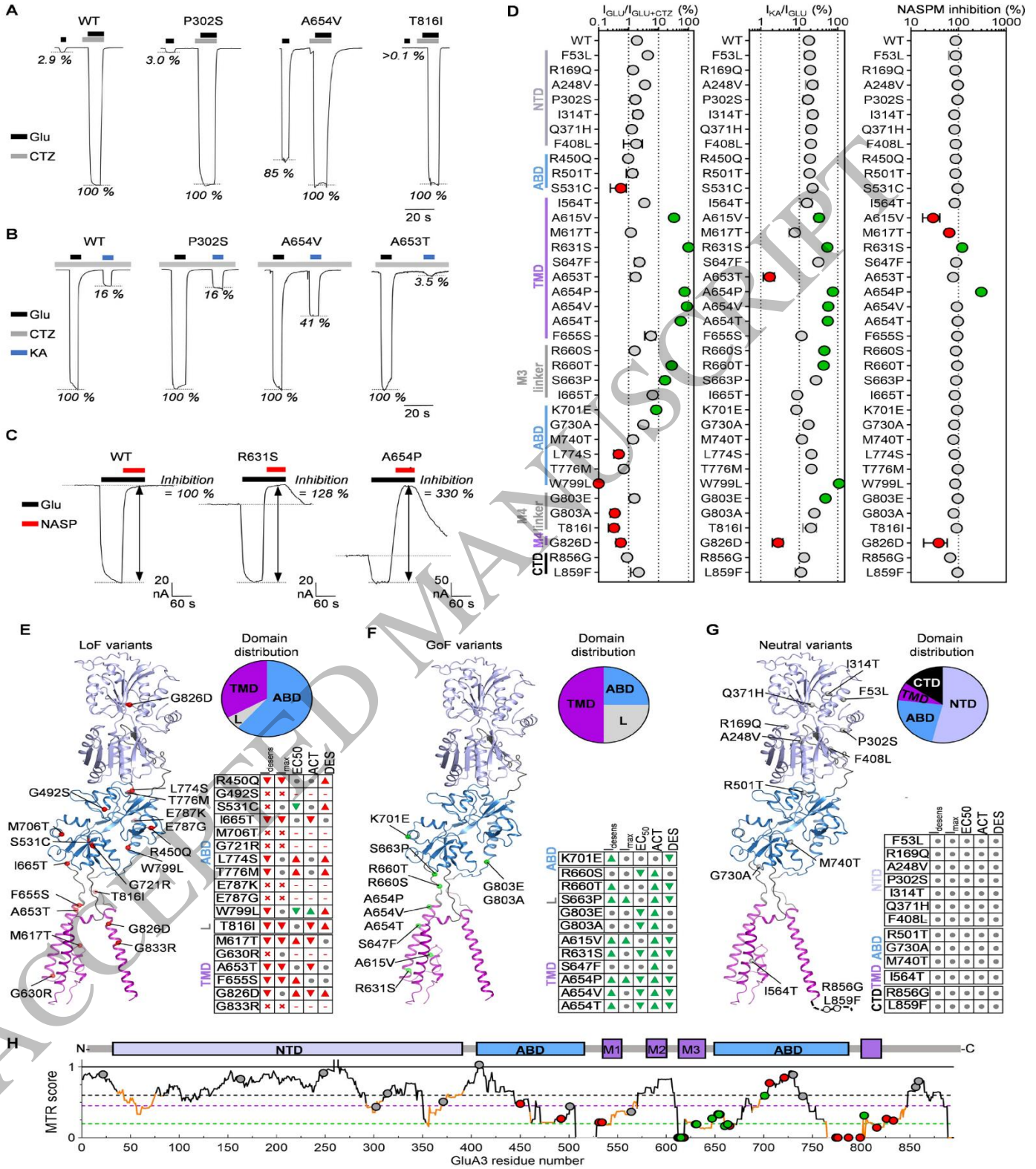


Figure 2
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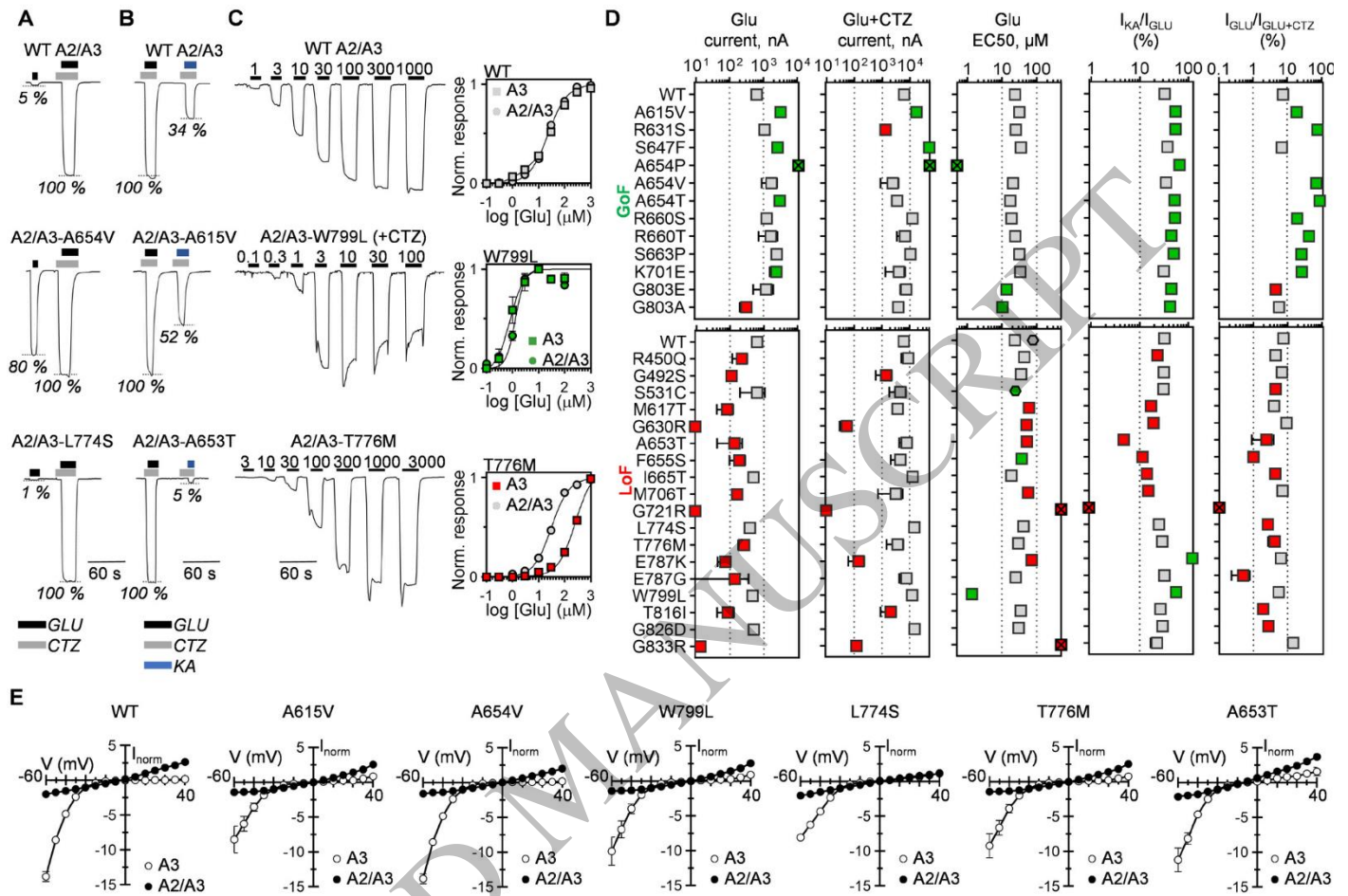


Figure 3
185x127 mm (x DPI)

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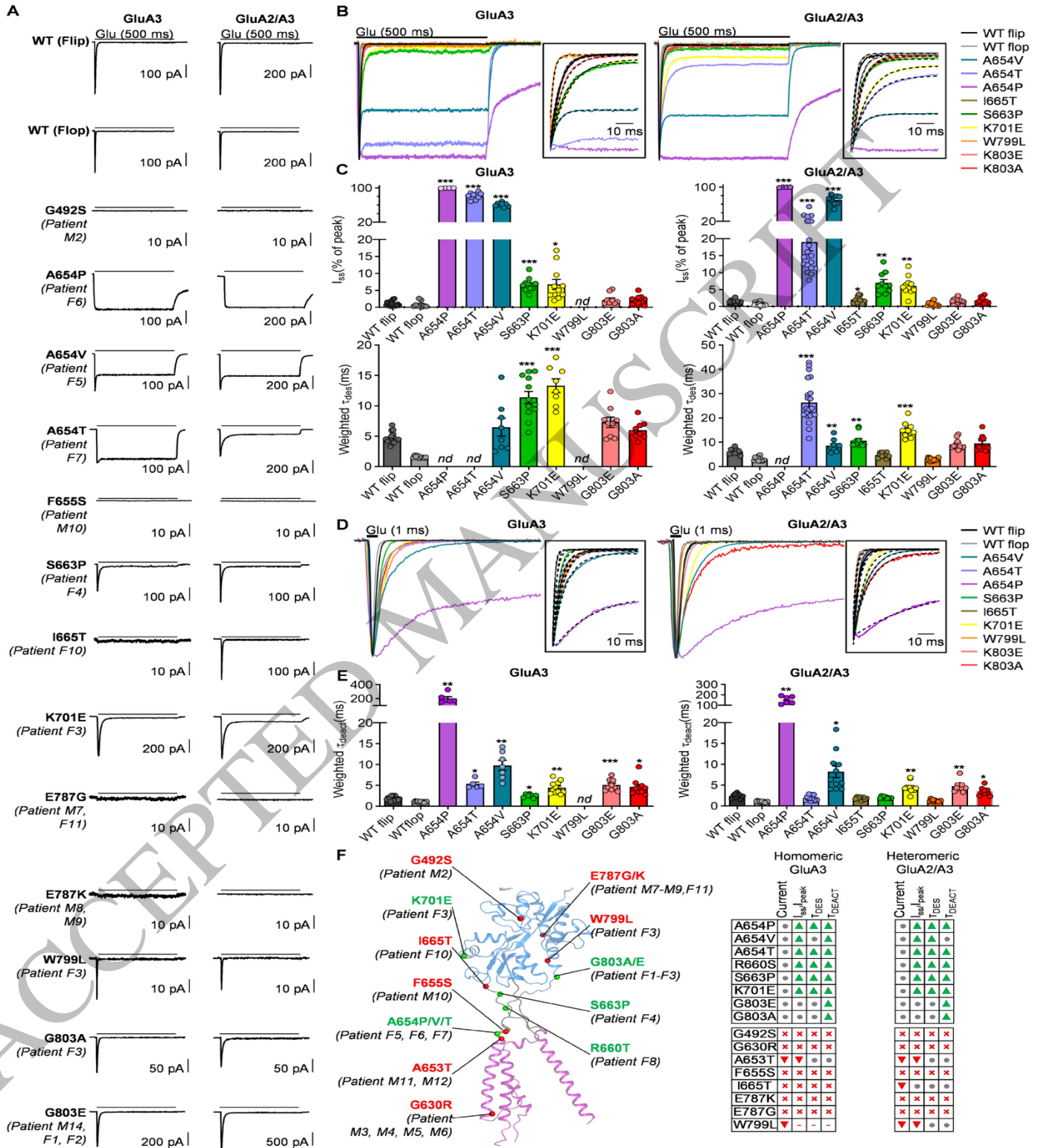


Figure 4
185x247 mm (x DPI)

1
2
3
4

A

		Female patients (variant)			Male patients (variant)		F4(S663P) F5(A654V) F6(A654P) F7(A654T) F8(R660T) F3(K701E)	
		F10(I665T)	F11(E787G)	F3(W799L)	F1-F2(G803E)	F3(K701E)		
		M1(Q371fs)	M2(G492S)	M3-6(G630R)	M10(F655S)	M7(E787G)	M11-M12(A653T)	M13(G803A) M14(G803E)
		M8-9(E787K)	M11-M12(A653T)	M13(G803A)	M14(G803E)			
		LoF	Severe	Mild	Mild	Severe	GoF	
Receptor phenotype		Peak current	complete loss	decreased	no change	increased/no change		
		Steady-state current	complete loss	decreased	no change	increased		
		Activation	-	decreased	increased	increased		
		Desensitization	-	increased/no change	decreased	blocked/decreased		
		Deactivation	-	unknown/no change	slowed	slowed		
		Glu sensitivity	-	increased/no change	increased	increased		
Clinical phenotype		Hypotonia	9(12)	3(3)	0(4)	0(6)		
		Hypertonia	1(12)	0(3)	4(4)	6(6)		
		Hyperekplexia	0(12)	0(3)	1(4)	4(6)		
		Sleep disturbance	7(12)	3(3)	1(4)	2(6)		

B

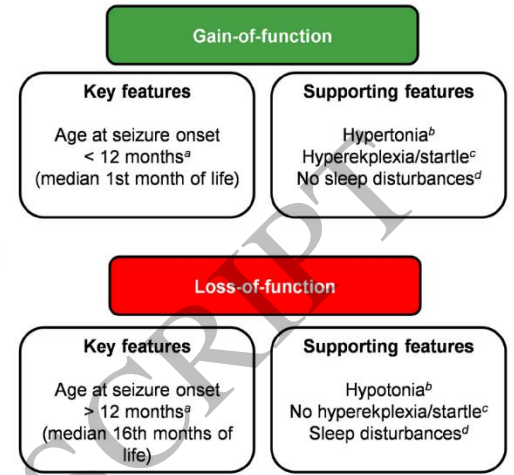


Figure 5
177x80 mm (x DPI)

1
2
3

ACCEPTED MANUSCRIPT