Glutamatergic transmission and receptor expression in the synucleinopathy h-α-synL62 mouse model: Effects of hydromethylthionine

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Abbreviations: α-Syn, alpha-synuclein; AMPA, alpha-amin-3-hydroxy-5-methyl-4-isoxazole propionic acid receptor; AD, Alzheimer’s disease; ChAT, choline acetyltransferase; COX IV, Cytochrome c oxidase subunit 4; DLB, Dementia with Lewy bodies; GluA1, glutamate ionotropic receptor AMPA type subunit 1; GluA2, glutamate ionotropic receptor AMPA type subunit 2; GluA3, glutamate ionotropic receptor AMPA type subunit 3; GluA4, glutamate ionotropic receptor AMPA type subunit 4; GluN1, glutamate ionotropic receptor NMDA type subunit 1; GluN2A, glutamate ionotropic receptor NMDA type subunit 2A; GluN2B, glutamate ionotropic receptor NMDA type subunit 2B; mGLUR, metabotropic glutamate receptor; MTEP, 3-((2-Methyl-4-thiazolyl)ethynyl)pyridine hydrochloride; HMTM, N3, N7, N10-tetramethyl-10H-phenothiazine-3, 7-diaminium bis(methanesulfonate) (leuco-methylthioninium bis(hydromethanesulfonate), hydromethylthionine mesylate; NMDAR, N-Methyl-D-aspartate receptor; PD, Parkinson’s disease; PSD-95, Postsynaptic density protein 95; SNARE, N-ethylmaleimide-sensitive factor attachment protein receptor; Syn-1, Synapsin-1; Syn-2, Synapsin-2; Syn-3, Synapsin-3; Syn-4, Synaptophysin-1; SNAP-25, Synaptosomal-associated protein, 25 kDa; Sntx-1, Syntaxin-1; VAMP-2, Vesicle-associated membrane protein 2; VGLUT, vesicular glutamate transporter.

ARTICLE INFO

Keywords:
Mouse model
Parkinson’s disease
α-Synuclein
Synaptosomes
Glutamate
Hydromethylthionine

ABSTRACT

The accumulation of alpha-synuclein (α-Syn) into Lewy bodies in cortical and subcortical regions has been linked to the pathogenesis of synucleinopathies such as Parkinson’s disease (PD) and dementia with Lewy bodies (DLB). While there is a strong link between synuclein aggregates and the reduction in dopamine function in the emergence of PD, less is known about the consequences of α-Syn accumulation in glutamatergic neurons and how this could be exploited as a therapeutic target. Transgenic h-α-synL62 (L62) mice, in which synuclein aggregation is achieved through the expression of full-length human α-Syn fused with a signal sequence peptide, were used to characterise glutamatergic transmission using a combination of behavioural, immunoblotting, and histopathological approaches. The protein aggregation inhibitor hydromethylthionine mesylate (HMTM) alone, or in combination with the glutamatergic compounds 3-((2-Methyl-4-thiazolyl)ethynyl)pyridine hydrochloride (MTEP) and memantine, was used to target α-Syn aggregation. We show that accumulation of α-Syn aggregates in glutamatergic synapses affected synaptic protein expression including metabotropic glutamate receptor 5 (mGLUR5) levels and ratio of N-methyl-D-aspartate (NMDA) receptor subunits GluN1/GluN2A. The ratio of NMDA receptor subunits and levels of mGLUR5 were both normalised by HMTM in L62 mice. These alterations, however, did not affect glutamate release in synaptosomes derived from L62 mice or behavioural endpoints following pharmacological manipulations of glutamate functions. Our results confirm that HMTM acts in the L62 mouse model of PD as an inhibitor of pathological aggregation of synuclein and show that HMTM treatment normalises both the ratio of NMDA receptor subunits and mGLUR5 levels. These findings support the potential utility of HMTM as a disease-modifying treatment for PD aiming to reduce synuclein aggregation pathology.
1. Introduction

Parkinson’s disease (PD) is the most common movement disorder in humans [1]. It is characterised by bradykinesia, rigidity and tremor, and these motor symptoms are related to dopamine depletion caused by a progressive loss of dopaminergic neurones [2]. PD is further associated with a broad spectrum of non-motor symptoms, experienced by most patients, such as cognitive deficits, loss of smell, and depression [3,4]. Alpha-synuclein (α-Syn) has been implicated in regulating synaptic vesicle mobilization and soluble N-ethylmaleimide-sensitive factor attachment protein receptor (SNARE) complex assembly and its regulatory actions are necessary to maintain homeostasis at synapses during intense activity, especially in dopaminergic neurons (reviewed in [5,6]). Increased expression of α-Syn, however, reduces neurotransmitter release and modulates synaptic transmission via neurotransmitter receptor activation [7,8]. The accumulation of α-Syn in Lewy bodies in cortical and subcortical regions has been strongly linked to the pathogenesis of PD [9-11]. While there is unequivocal evidence for a reduction in dopamine function in the emergence of PD, the role of α-Syn aggregation on non-dopaminergic neurotransmitter systems such as glutamatergic, cholinergic, serotonergic, and noradrenergic circuits is less clear [12,13]. Recent evidence suggests that the accumulation of α-Syn aggregates in synaptic terminals precedes neuronal loss and that these α-Syn species impair several steps of synaptic neurotransmission related to synucleinopathies (for review see [14]).

Dysfunction of the glutamatergic synapse has been described for many neurodegenerative disorders [15]. Glutamate is the predominant excitatory neurotransmitter in the mammalian brain and is involved in learning and memory [16]. Once released by the presynaptic endings, it acts mainly on three different post-synaptic receptors: N-methyl-D-aspartate receptor (NMDAR), α-amino-3-hydroxy-5-methyl-4-isoxazole propionic acid receptor (AMPAR) and metabotropic glutamate receptors (mGLUR) [17]. Less is known about a fourth class of glutamatergic receptors, the kainate receptors, the kainate receptors, their involvement in epilepsy, schizophrenia, and autism [18]. Excess glutamate in the synaptic space may lead to glutamatergic dysfunction, hyperexcitation and neuronal cell death, as seen in several inflammatory and neurodegenerative disorders [19].

Anomalies in the expression and/or function of the glutamatergic system have been reported in synuclein-related pathologies [20-24]. In mouse brain slices, electrochemical recordings at the level of presynaptic terminals showed that dopamine exerts an important tonic inhibition on glutamate which is essential for regulation of glutamate release [20]. This loss in tonic inhibition in the striatum of PD models may be the underlying cause for alterations in glutamatergic signaling and altered ratios of NMDAR subunits (for review see [15]). Overexpression of α-Syn has been associated with increased phosphorylation of subunits of NMDA and AMPA receptors, further contributing to glutamate toxicity (for review see [21]). In dementia with Lewy bodies (DLB), mGLUR levels were higher in subjects with pure DLB but lower in subjects with DLB-associated with Alzheimer’s disease (AD), when compared to control patients [22] and the levels of expression of mGLURs were correlated with the extent of AD pathology [23]. Another study conducted in patients with DLB revealed reduced vesicular glutamate transporter (VGLUT) and postsynaptic density protein 95 (PSD-95) (as well as several GABA receptors) expression in cortical tissue using RNA microarray [24]. These studies suggest that there may be anomalies in the expression and/or function of the glutamatergic system in synuclein-related pathologies.

Previous studies in different α-Syn-based mouse models have reproduced the dopaminergic deficit seen in humans, while we and others have additionally confirmed the accumulation of α-Syn aggregates in glutamatergic pyramidal cells [25-30]. Our L62 mice overexpress the wild-type form of the human α-Syn gene fused to a signal sequence to facilitate aggregation under the control of the mouse thy1-promoter. An earlier characterisation of L62 mice using biochemical and pathological methods confirmed the accumulation of proteinase K (PK)-resistant h-α-syn in both the cytoplasm and in synapses in immunohistochemically stained sections, but also in P2 fractions using western blotting (Schwab et al., 2018; Frahm et al., 2018). Different solubility patterns of h-α-syn were revealed through various biochemical extractions and oligomeric synuclein species confirmed by Thioflavin-binding assays. Furthermore, these mice have impaired dopamine and acetylcholine neurotransmission [30,31] and are therefore a useful tool for analysing important aspects of synucleinopathies. The L62 model was used in the present study to examine both glutamatergic function and the effects of targeting α-Syn pathology using the protein aggregation inhibitor hydromethylthionine mesylate (HMTM) either alone or in combination with glutamatergic compounds. We report that α-Syn aggregates accumulate in glutamatergic synapses in L62 mice and cause an increase in mGLUR5 and a loss of correlation between the NMDA receptor subunits GluN1/GluN2A. We further report that treatment with HMTM normalised both the ratio of NMDA receptor subunits and mGLUR5 levels. However, in the L62 model neither synuclein aggregation nor treatment with HMTM had any impact on synaptosomal glutamate release. Likewise, glutamate modulators 3-((2-methyl-4-thiazolyl)methyl)npyridine hydrochloride (MTEP), and memantine had little effect on behavioural endpoints in L62 in the presence or absence of HMTM.

2. Materials and methods

2.1. Animals and study design

All animal experiments were performed in accordance with the European Communities Council Directive (63/2010/EU) and approved by the German Animal Research Ethics Committee of LAGESO (Experiments I-III) or the UK Animals Scientific Procedures Act (1986) (Experiment IV) and comply with the ARRIVE guidelines 2.0 [32]. L62 mice have been behaviourally phenotyped using different behavioural paradigms and their dopamine and acetylcholine status revealed using in vivo microdialysis [30,31].

Male and female homozygous L62 and C57BL/6J wild-type litters were bred commercially in individually ventilated cages (Forschungseinrichtung fuer Experimentelle Medizin (FEM), Berlin, Germany) and delivered by truck/plane to the experimental facilities in Berlin (Germany) or Aberdeen (UK) at least 7 days prior to commencement of experimental work. They were housed by genotype and sex in small colonies up to 6 mice in open housing (Macrolon type III) with corncob bedding, paper strips and cardboard tubes as enrichment (cleaning once per week). Holding rooms were at constant temperature (20–22 °C), humidity (60–65%), and air exchange rates (17–20 changes/h) with 12 h light/dark cycle (lights on at 6 am Berlin/ 7 am Aberdeen) and animals had free access to food and water. Mice were 4–6 months of age at experimental start. An overview of animal details, drug treatments, and experimental layouts is given in Table 1.

Four different experiments were conducted: In Experiment I (12 wild-type and 12 L62 male subjects; n = 6 per group), mice received HMTM or vehicle, and selected synaptic proteins were analysed in synaptosome-enriched pellet fractions (Figs. 1–4). In Experiment II (48 wild-type and 41 L62 male subjects; n = 9–12 per group), mice were treated with HMTM/vehicle and additionally with a single dose of MTEP and underwent behavioural testing in the open field (Fig. 5). In Experiment III (47 wild-type and 45 L62 male subjects; n = 11–12 per group), mice were administered HMTM/vehicle together with memantine dissolved in the drinking water and were tested behaviourally in the light dark box (Fig. 6). In Experiment IV (15 wild-type and 12 L62 female subjects), mice did not receive any drug treatment, and synaptic glutamate release was assessed in enriched functional synaptosomes (Fig. 7). Mice were assigned to different study cohorts based on their body weight with equal average body weight for each group at the start of experiments.
**Table 1**

Study groups and cohort sizes. OF: open field, LDB: light dark box, MEM: memantine. n: number of mice.

| Experiment I (HMTM - Synaptic proteins) - Figs. 1–4 |
|-----------------------------------------------------|
| Sex | Age at start | Genotype | n vehicle | n HMTM | n total |
|-----------------|-------------|----------|------------|----------|--------|
| Male            | 6 months    | wild-type | 6          | 6        | 12     |
|                 |             | L62      | 6          | 6        | 12     |

| Experiment II (HMTM and MTEP - OF) - Fig. 5 |
|---------------------------------------------|
| Sex | Age at start | Genotype | n vehicle + saline | n vehicle + MTEP | n HMTM + saline | n HMTM + MTEP | n total |
|-----------------|-------------|----------|-------------------|------------------|----------------|---------------|--------|
| Male            | 4 months    | wild-type | 12                | 12               | 12             | 12             | 48     |
|                 |             | L62      | 9                 | 11               | 11             | 10 (9⁺)        | 41 (40⁺) |

| Experiment III (HMTM and MEM - LDB) - Fig. 6 |
|----------------------------------------------|
| Sex | Age at start | Genotype | n vehicle + water | n vehicle + MEM | n HMTM + water | n HMTM + MEM | n total |
|-----------------|-------------|----------|------------------|---------------|---------------|-------------|--------|
| Male            | 4 months    | wild-type | 12                | 11             | 12             | 12             | 47     |
|                 |             | L62      | 11 (10⁺)          | 11             | 12 (11⁺)       | 11             | 45 (43⁺) |

| Experiment IV (Glutamate release) - Fig. 7 |
|-------------------------------------------|
| Sex | Age at start | Genotype | n (+EGTA) | n total |
|-----------------|-------------|----------|------------|--------|
| Female          | 6 months    | wild-type | 15 (13⁺)  | 15 (13⁺) |
|                 |             | L62      | 12         | 12     |

¹ Actual n included for behavioural/glutamate release analyses after removal of outliers identified by Grubb’s test.

Power calculations were originally conducted using the power calculator tool [http://www.anzmtg.org/stats/PowerCalculator/PowerANOVA](http://www.anzmtg.org/stats/PowerCalculator/PowerANOVA) that was available online at the time these studies were planned with alpha = 0.05, beta = 0.2, effect size delta = 0.5 and power = 0.8 settings. We recently verified them with [https://www.stat.ubc.ca/~rollin/stats/ssize/n2.html](https://www.stat.ubc.ca/~rollin/stats/ssize/n2.html). Experimenter for behavioural testing, glutamate release studies and histopathology were not blinded to genotype/treatment details. Experimenters for protein quantification studies were blinded to drug treatment details.

### 2.2. Drugs and treatments

N3,N7,N7',N7'-Tetramethyl-10H-phenothiazine-3,7-diaminioquinine (methanesulfonate) (leuco-methylthioninium bis(hydromethanesulfonate); hydromethylthionine mesylate; HMTM) was supplied by TauRx Therapeutics Ltd., Aberdeen, UK at a purity >99% (Exp. 1 & 3: batch 800234810; Exp. 2: batch 7580CL-15). Treatment cohorts were dosed with HMTM or vehicle (argon-sparged deionised water) via oral gavage at a volume of 5 ml/kg body weight. Gavaging was performed in the morning between 8 and 10 a.m. for 5 days per week (Monday-Friday) at a dose of 5 mg/kg HMTM or vehicle. HMTM was prepared daily and administered within 20 min of dissolution in vehicle. Chronic treatment with HMTM lasted up to 7 weeks. HMTM was used alone (Experiment I), with 3-(2-Methyl-4-thiazolyl)ethyl)phenylidine hydrochloride (MTEP) (Experiment II) or with memantine (Experiment III) as stated above. MTEP was supplied by Tocris Bioscience (Bristol, UK, #2921, batch No. 1). MTEP is a selective mGLUR5 antagonist [33]. Treatment cohorts were dosed intraperitoneally with MTEP or saline (Experiment II). Immediately after injection, mice were released into the open field for behavioural testing (see below). MTEP was administered at 5 ml/kg body weight at a dose of 2.5 mg/kg, and the control group was treated with saline (0.9% w/v). MTEP solution was prepared fresh in saline shortly before administration. The concentration of MTEP administered was based on previous work indicating induction of hyperlocomotion in mice at this concentration [34].

Memantine hydrochloride (memantine) was purchased from Tocris Bioscience (#0773, batch No. 5). It is a widely used anti-AD treatment acting via inhibition of NMDA receptors [16]. Memantine was administered orally in the drinking water at a dose of 20 mg/kg body weight (Experiment III). The control group received drinking water without memantine. Based on the approximate daily water intake of 5 ml per mouse, and an average mouse body weight of 25 g, memantine solutions were prepared at a concentration of 0.1 mg/ml. Solutions were prepared twice a week in the morning based on the stability of memantine in water at room temperature [35]. Chronic treatment with memantine continued for 5 weeks. Previous studies have shown that 20–30 mg/kg/day oral administration of memantine via drinking water in mice produces a therapeutically relevant plasma concentration with of about 1 μmol [36–39].

### 2.3. Behavioural testing in the open field and the light dark box

The open field arena consisted of a grey Perspex square (43 cm × 23 cm × 40 cm: L x W x H), was placed 75 cm above the ground and surrounding cues were obscured by white curtains. Mice were released at the centre of the arena and allowed to move freely for up to 30 min. Movement was recorded by a monochrome overhead CCTV camera (sampling rate 12 Hz). Raw video files were stored as Moving Picture Experts Group (MPEG), and analysed using EthoVision XT10 (Noldus IT, Wageningen, Netherlands). The overall activity (distance moved in cm) was extracted and analysed as the primary readout.

The light dark box was composed of a grey Perspex box (43 cm × 26 cm × 26 cm: L x W x H), placed 75 cm above the ground and surrounded by white curtains. The box was divided into two equal-sized areas separated by a partitioning wall containing an aperture to enable free access to either side. One compartment, the dark zone, was covered by a lid while the second one remained open and represented the light zone. Mice were released in one corner of the light zone and allowed to explore both compartments freely for 10 min. Ambulation within the light compartment was recorded by a monochrome overhead CCTV camera (sampling rate 12 Hz), raw data files were stored as MPEG, and analysed using EthoVision XT10. The distance moved (cm), the time spent (s) and the velocity cm/s in the light compartment were extracted as primary readouts for analysis.

Between animals, arenas were cleaned using 70% ethanol before
Fig. 1. Human α-Syn is expressed in glutamatergic synapses in L62 mice and is decreased in crude synaptosomes by HMTM. Human-α-Syn (green) co-localises with the presynaptic glutamatergic marker VGLUT1 (red), seen as yellow puncta in the merged image of the immunofluorescence micrographs taken from striatal sections (A). To investigate the influence of HMTM on human-α-Syn and other synaptic proteins of interest, wild-type and L62 mice were administered with HMTM for 6 weeks, and at the end of the study brains collected for extraction of P2 (B). Details of the study are shown in Table 1. For biochemical analyses, crude synaptosomes were extracted using the illustrated protocol (C) detailed in the methods. The enrichment of the crude synaptosomes was verified by labelling of the resulting fractions S2 and P2 with antibodies against selected synaptic proteins, that were separated by Tris-glycine SDS-PAGE (D). For quantification of α-Syn in P2, proteins were separated by Tris-tricine SDS-PAGE; representative blots for human- and mouse-α-Syn are shown (E, arrow indicates α-Syn monomer) and quantification of human- (F) and mouse-α-Syn (G) in these crude synaptic fractions from wild-type and L62 mice, treated with either vehicle or HMTM are illustrated. Densitometric quantification of blots was conducted using the Image Lab software and normalised to beta-tubulin. Individual values and group means are plotted, and statistical analyses were conducted using unpaired t-test. Additionally, a correlation analysis was performed between human- and mouse-α-Syn (H) for L62 mice receiving either vehicle (green) or HMTM (blue). α-syn: α-synuclein, WT: wild-type, M: molecular weight marker. Number of mice per group = 6.
introducing the next subject. Behavioural assessments took place during the last week of drug dosing between 9 am and 3 pm and mice were sacrificed one to two hours after the last drug administration where applicable.

2.4. Animal sacrifice and collection of brain tissue

Mice were 5–7 months when sacrificed by cervical dislocation. The top of the skull was exposed, and the overlying bone plates removed to allow harvest of the brain in an intact state. Brains were then rapidly extracted, the cortex dissected and snap frozen in liquid nitrogen for protein expression studies (Experiment I) or immediately processed further (excluding olfactory bulbs and cerebellum) for preparation of functional synaptosomes as described below (Experiment IV). For histopathological studies (Experiment III), brains were fixed overnight at room temperature (RT) in 10% (v/v) neutral-buffered formalin, embedded in paraffin and sectioned on a rotary microtome (HM 325, Leica Biosystems, Wetzlar, Germany) at 5 μm thickness.

2.5. Immunohistochemistry and manual counting of choline acetyltransferase (ChAT)-positive neurones

Coronal brain sections, 5 μm thick, were collected from front brain areas (corresponding to sections Bregma +0.74 mm for striatum of the mouse brain atlas [40]) using a rotary microtome (HM 325, Leica Biosystems), mounted onto glass slides (three sections per slide), deparaffinised, boiled for antigen retrieval in 10 mM citric buffer, pH 6.0, and then incubated in 0.3% (v/v) hydrogen peroxidase solution. Sections were blocked for 20 min in blocking solution (0.1% (w/v) bovine serum albumin (BSA) in phosphate buffered saline (PBS), pH 7.4), incubated in primary antibody (anti-choline acetyltransferase (ChAT)), H-95, diluted 1:200, Santa Cruz Biotechnology, Dallas, USA), followed by incubation in biotinylated goat anti-rabbit IgG secondary antibody (Dako Denmark, Glostrup, Denmark). Primary and secondary antibodies were diluted in blocking solution and reactions were conducted for 1 h at RT. Sections were then developed using diaminobenzidine solution (Dako Denmark) and embedded in Neo-Mount (Merck Millipore, Burlington, MA, USA). Images were taken using a light microscope at a 100× magnification (Axio imager M1, Carl Zeiss, Jena, Germany) and ChAT-positive neurones were counted manually in the striatum and the medial septum / diagonal band of Broca (MS/DBB).

2.6. Immunofluorescence

Five-μm coronal sections were collected for striatal areas (corresponding to sections Bregma +0.74 mm, Mouse Brain Atlas [40]) from randomly selected wild-type and L62 mice. The sections were de-waxed, boiled in 10 mM citrate buffer, blocked for 1 h at RT in blocking buffer (5% (v/v) normal goat serum in PBS, pH 7.4), containing 0.3% (v/v) Triton X-100) and incubated overnight at 4°C in primary antibody cocktail (human-α-Syn (Syn 204, Santa Cruz Biotechnology, Dallas, USA), diluted 1:100 and the vesicular glutamate transporter-1 (VGLUT1) (#135302 Synaptic Systems, Goettingen, Germany), diluted 1:1000 in blocking buffer). The next day, sections were washed 3 × 10 min with PBS, incubated for 1.5 h at RT in fluorochrome-conjugated secondary antibodies (Alexa Fluor® 488-conjugated donkey anti-mouse IgG and
The image contains a series of graphs and data representations. Here is a breakdown of the main elements:

**A**
- A gel image showing protein bands for different treatments: Vehicle (WT, L62), HMTM (WT, L62).
- Proteins targeted include mGLUR1, mGLUR5, GluN1, GluN2A, GluN2B, GluA1, pGluA1, GluA2, pGluA2, GluA3, GluA4, and Loading.

**B**
- Relative protein level (au) graphs for mGLUR1, mGLUR5, GluN1, GluN2A, GluN2B, GluA1, pGluA1, GluA2, pGluA2.

**C**
- Scatter plot showing the relationship between GluN2A and GluN1 with a line of best fit.
  - $R^2 = 0.33$ for wild-type, vehicle.
  - $R^2 = 0.67$ for L62, vehicle.

**D**
- Scatter plot showing the relationship between GluN2A and GluN1 with a line of best fit.
  - $R^2 = 0.05$ for wild-type, HMTM.
  - $R^2 = 0.40$ for L62, HMTM.

**E**
- Scatter plot showing the relationship between GluN2B and GluN1 with a line of best fit.
  - $R^2 = 0.01$ for wild-type, vehicle.

**F**
- Scatter plot showing the relationship between GluN2B and GluN1 with a line of best fit.
  - $R^2 = 0.06$ for wild-type, HMTM.
  - $R^2 = 0.26$ for L62, HMTM.

**G**
- Bar graph showing the ratio of GluN1 to GluN2A.
  - Groups: wild-type, vehicle, L62, vehicle, wild-type, HMTM, L62, HMTM.
  - Statistical significance indicated with asterisks (*), n.s. (not significant).

The data suggests that there are notable differences in protein expression and ratios across different treatments and conditions, indicating potential changes in cellular signalling pathways.
Alexa Fluor® 568-conjugated goat anti-rabbit IgG, Thermo Fisher Scientific, Waltham, MA, USA; both diluted 1:500 in blocking buffer), α-entific, Waltham, MA, USA; both diluted 1:500 in blocking buffer), −

2.7. Protein extraction, electrophoresis, and immunoblotting

Crushed frozen cortical brain tissue (200 ± 25 mg) was mixed with 1500 μl ice-cold lysis buffer (5 mM HEPES, pH 7.4, 0.32 M sucrose, cOmplete protease-inhibitor cocktail tablets, and PhosSTOP phosphatase-inhibitor cocktail tablets) and homogenized with a tissue homogeniser (T25, IKA, Staufen, Germany) with 5 strokes on level 1 for 15 s each stroke [41]. The homogenate was then centrifuged for 10 min at 1000 x g and 4 °C. The pellet (P1) was discarded, and the supernatant (S1) centrifuged for 20 min at 12,000 x g and 4 °C. The resulting second supernatant (S2) and pellet containing the crude synaptosomes (P2) were used for further analyses (see Fig. 1). P2 was suspended in 500 μl PBS, pH 7.4 (137 mM NaCl, 2.7 mM KCl, 10 mM Na₂HPO₄, 1.8 mM KH₂PO₄, cOmplete protease-inhibitor cocktail tablets, and PhosSTOP phosphatase-inhibitor cocktail tablets). The protein concentration was determined using the Bradford reagent (Carl Roth, Karlsruhe, Germany) according to the manufacturer’s description. Both fractions were diluted to a final concentration of 5 μg/μl (P2 in PBS, around 750 μl final volume; S2 in lysis buffer, around 1300 μl final volume), aliquoted to avoid multiple thawing/freezing cycles and stored at −20 °C. S2 and P2 were used to confirm enrichment of synaptosomes. Thereafter, P2 was used to quantify synaptic proteins in brain tissue derived from Experiment I.

Samples (20 μg per lane) were subjected to tricine or glycine SDS-PAGE. The tricine gels (10%) were run using a discontinuous buffer. Proteins from glycine gels were transferred to PVDF membranes for electroblotting overnight at 4 °C and 0.4 mA/cm² in tricine transfer buffer (300 mM Tris, 6% (v/v) acetic acid, pH 8.6). Afterwards, membranes were blocked for 1 h at RT in blocking solution (4% (w/v) BSA in TBS with 0.2% (v/v) Tween-20), incubated overnight at 4 °C in primary antibody, diluted in blocking solution, washed 3 times 10 min in TBS-T (TBS with 0.2% (v/v) Tween-20) and incubated for 1 h at RT in appropriate secondary antibody diluted in blocking solution. After washing 3 more times in TBS-T, membranes were overlaid for 1 min with ECL solution (101.5 mM Tris pH 8.5, 1.25 mM luminol, 200 μM p-coumaric acid, 0.01% (v/v) H₂O₂). The chemiluminescence signals were detected by the ChemiDoc Imaging System (Bio-Rad Laboratories), and the Image Lab software (version 6.1, Bio-Rad Laboratories) applied for densitometric quantification. The membranes from tricine gels were labelled with antibodies against human-α-Syn and mouse-α-Syn, and additionally with beta-tubulin as loading control for normalisation. The membranes from glycine gels were used for all other antibodies and total protein loading (stain-free gels) was used for normalisation. Details of antibodies used are given in Table 2.

2.8. Glutamate release

Naive mice were killed by cervical dislocation and the brains carefully removed in an intact state to extract synaptosomes [41,42]. Whole brains were quickly rinsed in 20 ml ice-cold sucrose/EDTA/tris solution (0.32 M sucrose, 1 mM EDTA, 5 mM tris, pH 7.4), transferred to another tube with 10 ml fresh sucrose/EDTA/tris solution and briefly minced with scissors. The tissue was then homogenized with six strokes at 700 rpm (Eurostar 20 homogeniser, IKA, Staufen, Germany), spun in a pre-cooled 50 ml centrifugation tube for 10 min at 2800 x g and 4 °C. The supernatant (S1) was removed and kept on ice; the pellet was suspended with 10 ml sucrose/EDTA/tris, centrifuged for a further 10 min at 2800 x g and 4 °C and the second supernatant (S2) pooled with the first supernatant. Combined supernatants S1 and S2 were centrifuged for 15 min at 13,000 x g and 4 °C and the final pellet (P2) suspended in 6 ml ice-cold Krebs solution (118.5 mM NaCl, 4.7 mM KCl, 1.2 mM MgSO₄, 10 mM glucose, 1 mM Na₂HPO₄, 20 mM HEPES, pH 7.4). The protein concentration in P2 was determined using the Lowry method (Bio-Rad) according to the manufacturer’s description. The synaptosome solution was then diluted in Krebs solution to a final concentration of 0.6 mg/ml and used for the glutamate release assay.

For glutamate release, a potassium (K⁺) chloride dependent enzyme-linked assay was used. Synaptosomes (0.6 mg in 2 ml) were diluted in Krebs solution, either in the presence of Ca²⁺ (0.4 mM CaCl₂) or in its absence (including 1 mM EGTA (ethylene glycol-bis-(β-aminoethyl)ether)-N,N,N',N'-tetraacetic acid, Sigma-Aldrich). Enzymatic reactions were carried out at 37 °C in 3.5 ml flat-bottomed cuvettes (StarNova Scientific Ltd) on an 8 mm magnetic stirrer (Fisher Scientific, UK) in the sample chamber of the spectrofluorometer (Photo Technology International DeltascanTM Model 4000-45). Experiments were started at t = 0 mins by the addition of NADP⁺ (1 mM; Sigma-Aldrich, Burlington, MA, USA) to synaptosomes. Once the synaptosome suspension was equilibrated, glutamate dehydrogenase (50 U/ml) was added at t = 60 mins and glutamate release initiated by KCl (30 mM) at t = 240 mins. Fluorescence recordings took place using λex = 340 nm, λem = 460 nm. In general, all experiments followed the same timeline and control (glutamate (0.5 mM) was added at t = 660 mins and recordings terminated at t = 900 mins. Data were continuously collected (1 Hz sampling rate) and original traces saved in ASCII format (Lab Master Series Software, version 1.22, 1986; Scientific Solutions Inc., Mentor, OH, USA) and exported to Microsoft Excel. The raw absorbance values were then converted to glutamate release (according to 0.6 mg/ml per synaptosome) and all traces were aligned to 240 min. Next, values at t = 660 min to t = 900 min in the presence of external 0.5 mM glutamate standard were quantified and then normalised to fluorescence derived from wild-type mice. Maximal release was calculated from t = 660 minus those from t = 240 for K⁺-evoked glutamate release. To reduce noise artefacts, traces were smoothed, using 2nd order polynomial smoothing (GraphPad Prism software version 8.00; GraphPad Software Inc., San Diego, CA, USA).

2.9. Data analyses

For immunoblotting and behavioural data, individual values, group mean, and S.E. (standard error) were plotted. Glutamate release data is shown as smoothed traces over 900 s and cumulative maximal release as group mean and S.E. Statistical analyses were conducted using 2-way or
3-way analysis of variance (ANOVA) with Bonferroni multiple comparison correction post-hoc test or unpaired t-test where appropriate. Further, correlation analyses using Pearson correlation between the synaptic proteins (raw expression values) were conducted. Outliers were identified by Grubb’s test and a total of five outliers (Table 1) were identified: one outlier in Experiment II (one L62 receiving HMTM and MTEP), two in Experiment III (one L62 receiving vehicle and drinking water, and one L62 receiving HMTM and drinking water), and two outliers in Experiment IV (two wild-type). GraphPad Prism software (version 8.00; GraphPad Software Inc.) was applied for all statistical analyses and for generation of graphs and heatmaps. Differences were considered significant at $p < 0.05$ and only significant outcomes are reported in the text.

3. Results

3.1. The abundance of human-$\alpha$-Syn monomers is increased in L62 crude synaptic fractions

We have previously reported that L62 mice show widespread human-$\alpha$-Syn immunoreactivity in brain and spinal cord, with several neuronal populations having high expression levels, including glutamatergic and cholinergic neurons in cortex and striatum [30,31]. We now show that human-$\alpha$-Syn also accumulates in glutamatergic synapses. Labelling of frontal brain sections with antibodies against human-$\alpha$-Syn (green) and VGLUT1 (red), a marker for glutamatergic synapses, shows co-localisation of both proteins as yellow puncta in the merged image (Fig. 1A). In Experiment I (Fig. 1B) we measured the levels of human-$\alpha$-Syn accumulation in crude synaptosomal fractions obtained from brain extracts following the procedure depicted in Fig. 1C in L62 and wild-type mice with and without HMTM treatment. Enrichment of synaptosomes in P2 was confirmed for several presynaptic markers (e.g., synapsin-1, syntaxin-1, SNAP-25, and others), as well as the post-synaptic marker PSD-95 and the mitochondrial marker Cox IV (Fig. 1D). On the other hand, beta-actin was significantly reduced in the P2 and enriched in the S2 fraction (Fig. 1D). Additional calibration experiments to permit quantification and measurement of these proteins are shown in Supplementary Fig. 1. Within the tested range of protein loading (up to 20 $\mu$g), linearity was confirmed for reactivity with the antibody at the dilutions applied. A total protein loading of 20 $\mu$g was chosen to quantify the synaptic proteins of interest and the corresponding dilutions of the different antibodies are provided in Table 2. Quantitative analysis of representative immunoblots (Fig. 1E) confirmed the expected increase in human-$\alpha$-Syn in vehicle-treated L62 mice relative to wild-type litters. Treatment with HMTM at 5 mg/kg reduced human-$\alpha$-Syn immunoreactivity to levels seen in wild-type mice (Fig. 1F). Mouse-$\alpha$-Syn levels were not affected by HMTM (Fig. 1G). Interestingly, there was a near significant negative correlation between human-$\alpha$-Syn and mouse-$\alpha$-Syn in L62 mice receiving vehicle (Fig. 1H, correlation coefficient $R^2 = 0.57$ and $p = 0.08$), but not in HMTM-treated L62 mice (Fig. 1H, correlation coefficient $R^2 = 0.06$ and $p = 0.64$). Changes in body weights did not differ between cohorts after the 6 weeks treatment with HMTM (Supplementary Fig. 2A).

3.2. The abundance of synaptic proteins and subunits of glutamate receptors is different in crude synaptic fractions from L62 mice

Levels of several proteins involved in structural (pre-synaptic, Fig. 2) and glutamate signaling functions (post-synaptic, Fig. 3) were examined in the same P2 fractions (Experiment I, see Fig. 1B). There were no differences between groups in levels of synapsin-1, VAMP-2, synaptophysin-1, synapsin-2, or SNAP-25 (Fig. 2A). There was an interaction effect for syntaxin-1 (genotype x treatment F(1,20) = 4.427; $p = 0.048$, Fig. 2B) indicating an increase in syntaxin-1 only in L62 mice following HMTM treatment (see hashtag, Fig. 2B). Similarly, PSD-95 was increased only in L62 following HMTM treatment (genotype x treatment F(1, 20) = 7.179; $p = 0.014$, Fig. 2B, see hashtag relative to L62 vehicle, and see asterisks for comparison with HMTM-treated wild-type mice).

As shown in Fig. 3A, the majority of glutamatergic proteins examined did not differ between genotypes and treatments. However, L62 mice had significantly elevated levels of mGLUR5 (main effect of genotype F(1, 20) = 9.870; $p = 0.005$, Fig. 3B). Treatment with HMTM decreased mGLUR5 in both wild-type and L62 mice (main effect of treatment F(1, 20) = 8.487; $p = 0.009$, Fig. 3B). Furthermore, HMTM decreased the phosphorylation levels of AMPA subunit GluA2 in both wild-type and L62 mice similarly (main effect of treatment F(1, 20) = 6.394; $p = 0.020$, Fig. 3B). Interestingly, there was a significant negative correlation between NMDA receptor subunits GluN1 and GluN2A in vehicle-treated wild-type mice (Fig. 3C, correlation coefficient $R^2 = 0.67$ and $p = 0.045$), while no correlation was seen in vehicle or HMTM-treated L62 mice (Fig. 3C-D, correlation coefficient $R^2 = 0.33$ and $p = 0.233$ for vehicle-treated L62 and $R^2 = 0.05$ and $p = 0.66$ for HMTM-treated L62). Levels of NMDA receptor subunits GluN1 and GluN2B were unaffected either by genotype or treatment (Fig. 3E-F). Nevertheless, the ratio of NMDA receptor subunits GluN1 and GluN2A was normalised in L62 by HMTM treatment (genotype x treatment F(1, 20) = 18.91; $p = 0.029$, and asterisks for post-test Fig. 3G).

We used heatmapping to display the strength of statistical significance of pairwise correlations according to genotype and HMTM treatment. The findings are depicted in Fig. 4, in which the two vehicle conditions (Fig. 4A and B) and the two genotypes treated with HMTM (Fig. 4C and D) are compared. In wild-type mice, strong positive correlations were particularly obvious between presynaptic structural proteins including synapsins and synaptophysin and post-synaptic proteins such as PSD-95 and NMDA receptor subunits GluN2A and B, as well as AMPA glutamate receptors GluA1 in wild-type mice. Within the red rectangle in B, there was a high positive correlation for GluA3/4 with some NMDA receptor subunits such as GluN2A/B, GluA1, GluA3 and GluA4 in L62 mice.
A) Behaviour in the open field (MTEP and HMTM)

Male / 4 months / 48 wild-type and 41 L62

MTEP or saline (i.p.)

7 weeks

Group 1: vehicle (oral gavage)
Group 2: HMTM (oral gavage)
Group 3: vehicle (oral gavage)
Group 4: HMTM (oral gavage)

Behaviour open field

B) Vehicle vs. HMTM

Total distance open field (m)

- Wild-type
- L62

Genotype: ns
MTEP: p < 0.0001
Genotype x MTEP: ns
HMTM: ns
Genotype x HMTM: ns
MTEP x HMTM: ns
Genotype x MTEP x HMTM: ns

C) Vehicle

Wild-type, saline
Wild-type, MTEP
L62, saline
L62, MTEP

D) HMTM

Wild-type, saline
Wild-type, MTEP
L62, saline
L62, MTEP

(caption on next page)
Intriguingly, there is an almost complete loss of correlations for PSD-95, a stabilizer for NMDA receptors [43], with synaptic and other glutamate receptor proteins. On the other hand, there were strong positive correlations for GluA3/4 with some NMDA receptor subunits (see red rectangle in Fig. 4B) in L62 mice. Most of these positive correlations in L62 mice were weakened following HMTM treatment (Fig. 4D) with the correlation map appearing more scattered with few reaching statistical significance.
Fig. 7. Synaptic glutamate release in functional synaptosomes is similar between wild-type and L62 mice and depends on the presence of Ca²⁺ (Fig. 4C) but reduced the correlations between the glutamate receptor subunits. Very few (6 in total) significant correlations remained in L62 mice after long-term exposure to HMTM (Fig. 4D) with no clear pattern emerging.

### Table 2
List of antibodies used for immunoblotting.

| Primary antibodies       | Source            | Antibody-ID | Host | Dilution |
|--------------------------|-------------------|-------------|------|----------|
| Human-α-Syn (Syn 204) *#  | Santa Cruz Biotechnology | sc-32,280 | mouse | 1:100    |
| Mouse-α-Syn (D75A6) *#   | Cell Signaling Technology | 4179 | rabbit | 1:1000   |
| Beta-tubulin*             | Cell Signaling Technology | 15,115 | rabbit | 1:1000   |
| PSD-95                   | Cell Signaling Technology | 3450 T | rabbit | 1:1000   |
| Synaptin-1, Klon46.1     | Synaptic Systems   | 106,001 | mouse | 1:50,000 |
| Synaptin-2               | Cell Signaling Technology | 85,852 | rabbit | 1:10,000 |
| Synaptophysin-1          | Synaptic Systems   | 101,002 | rabbit | 1:10,000 |
| Syntaxin-1               | Abcam             | ab112198 | mouse | 1:50,000 |
| SNAP-25                  | Biolegend         | 805,001 | mouse | 1:50,000 |
| VAMP-2                   | Synaptic Systems   | 104,202 | rabbit | 1:50,000 |
| COX IV                   | Cell Signaling Technology | 4850 | rabbit | 1:1000   |
| β-actin                  | Santa Cruz Biotechnology | sc-1615 | goat | 1:5000   |
| mGLUR1                   | Cell Signaling Technology | 12,551 | rabbit | 1:1000   |
| mGLUR5                   | Abcam             | ab76316 | rabbit | 1:10,000 |
| GluN1                    | Cell Signaling Technology | 5704 | rabbit | 1:1000   |
| GluN2A                   | Cell Signaling Technology | 4205 | rabbit | 1:1000   |
| GluN2B                   | Cell Signaling Technology | 14,544 | rabbit | 1:1000   |
| GluA1                    | Cell Signaling Technology | 13,185 | rabbit | 1:1000   |
| pSer845-GluA1            | Cell Signaling Technology | 8084 | rabbit | 1:1000   |
| GluA2                    | Cell Signaling Technology | 5306 | rabbit | 1:1000   |
| pTyr669-GluA2            | Cell Signaling Technology | 3921 | rabbit | 1:1000   |
| GluA3                    | Cell Signaling Technology | 4676 | rabbit | 1:1000   |
| GluA4                    | Cell Signaling Technology | 8070 | rabbit | 1:1000   |

| Secondary antibodies (HRP-conjugated) | Source       | Antibody-ID | Host | Dilution |
|--------------------------------------|--------------|-------------|------|----------|
| Goat-anti-mouse                      | Agilent (Dako) | P0447 | goat | 1:5000   |
| Goat-anti-rabbit                     | Agilent (Dako) | P0448 | goat | 1:5000   |
| Rabbit-anti-goat                     | Agilent (Dako) | P0449 | goat | 1:5000   |

* These antibodies were used to label membranes from Tris-tricine gels. All other antibodies were used on membranes from Tris-glycine SDS-PAGE.

# We have explored human/mouse selectivity in multiple other commercial (Syn211, LB50, sc-7011R, sc-69977) and in-house antibodies (AB539, AB874, AB736). Due to the high sequence similarity between human and mouse α-Syn, none of them was species-specific.

The overall number of significant (p < 0.05) or strongly significant (p < 0.001) correlations ranked as follows: wild-type + HMTM > wild-type > L62 > L62 + HMTM. We found that the significant correlation between SNTX-1 and SNAP-25/SYN-2, as well as between SNAP-25 and synaptophysin-1 seen in wild-type mice (Fig. 4A) were absent in L62 mice (Fig. 4B). Correlations between the AMPA subunit GluA1 and the remaining AMPA subunits were similar between genotypes but stronger and thus significant between GluA1 and GluA3/4 in L62 (compare red highlighted areas in Fig. 4A and B). Furthermore, there was a significant correlation between PSD-95 and GluA1/phosphoGluA1 in wild-types, which was absent in L62, and instead PSD-95 was found to correlate with GluA2/phosphoGluA2.

In wild-type mice, HMTM exposure particularly enhanced the significance for correlations of structural and functional presynaptic proteins (Fig. 4C) but reduced the correlations between the glutamate receptor subunits. Very few (6 in total) significant correlations remained in L62 mice after long-term exposure to HMTM (Fig. 4D) with no clear pattern emerging.

### 3.3. The response pattern in open field and light dark box following challenge with glutamatergic antagonists in L62 mice is normal

Having established that accumulation of human-α-Syn in glutamatergic synapses in L62 produces a major disruption in the correlations that normally exist between structural proteins of the synapse and glutamate receptors, we went on to explore the functional consequences of these changes using different glutamatergic antagonists: MTEP for...
mGluR5 and memantine for NMDA receptors.

In Experiment II, mice were chronically treated with HMTM (controls received vehicle) for 7 weeks and an acute intraperitoneal injection of mTET/saline was administered prior to assessment of locomotor activity in the open field arena (Fig. 5A). The selective mGluR5 antagonist, MTEP, at a dose of 2.5 mg/kg, significantly stimulated ambulatory activity during thirty minutes of free exploration (Fig. 5B). Induction of locomotor hyperactivity by MTEP was comparable between genotypes, both in vehicle and HMTM-treated cohorts (3-way ANOVA: effect of MTEP F(1, 80) = 131.5; p < 0.0001). These effects are confirmed by representative video-tracks (Fig. 5C/D). Change of body weights at sacrifice did not differ for individual drug treatment groups, but there was an interaction effect for MTEP and HMTM (3-way ANOVA: effect of MTEP x HMTM F(1, 79) = 5.41; p = 0.023, Supplementary Fig. 2B).

In Experiment III, mice were exposed to memantine-containing or normal drinking water for a total of 5 weeks. During weeks 3–5, an additional daily oral dose of 5 mg/kg HMTM/vehicle was given to selected subgroups followed by behavioural assessment in the light dark box (Fig. 6A). The distance moved, the time spent, and the velocity in the light compartment, recorded via video-observation, were considered primary readouts for locomotion and anxiety in this behavioural paradigm. The distance moved, the time spent in the light zone and the velocity were all similar between treatment groups (Fig. 6B–D). Body weight change at sacrifice (Supplementary Fig. 2C), was significantly different between genotypes and due to treatment with memantine (3-way ANOVA: effect of MEM F(1, 84) = 57.41; p < 0.0001, effect of genotype F(1, 84) = 13.61; p = 0.0004, effect of MEM x genotype F(1, 84) = 22.18; p < 0.0001), and the membrane effect was greater in HMTM-treated cohorts (effect of MEM x HMTM F(1, 84) = 5.50; p = 0.021). Furthermore, to explore/exclude any effect of memantine on cholinergic tone, we quantified ChAT-positive neurones in basal forebrain regions and the striatum in L62 mice (Supplementary Fig. 3A/B, respectively). The number of cholinergic neurones was similar between L62 cohorts receiving the different drugs, both in MS/DBB (Supplementary Fig. 3C) and in striatum (Supplementary Fig. 3D).

3.4. Glutamate release in functional synaptosomes is intact in L62 mice

Given the lack of difference between wild-type and L62 mice in their behavioural responses to post-synaptically active glutamatergic antagonists, we examined glutamate release in synaptosomes prepared from naïve mouse brain tissues using a fluorochrome-based kit (Experiment IV, Fig. 7A). In wild-type mice, the glutamate release was significantly greater in the presence of Ca\(^{2+}\) compared to release when EGTA was added (Fig. 7B, main effect of Ca\(^{2+}\): F(1, 850) = 2575; p < 0.0001). In L62 mice, the glutamate release was likewise significantly greater in the presence of Ca\(^{2+}\) compared to when EGTA was added (Fig. 7C, main effect of Ca\(^{2+}\): F(1, 850) = 1387; p < 0.0001). Cumulative data show similar maximal glutamate release values for wild-type and L62 mice and confirm the Ca\(^{2+}\) dependence (Fig. 7D, main effect of Ca\(^{2+}\) F(1, 46) = 8.36; p = 0.006).

4. Discussion

We have reported previously that the L62 model of synucleinopathy is characterised by widespread accumulation of human-α-Syn in different neuronal populations of the brain including cortex, basal forebrain, striatum, and spinal cord. Synuclein pathology was particularly noted in cholinergic neurones and in glutamatergic pyramidal cells [30]. Treatment with the protein aggregation inhibitor HMTM reduced synuclein pathology in multiple brain regions and reversed some of the anxiety-related traits in these animals [44]. In the present report, we have extended our investigations of the L62 model with a particular focus on the glutamatergic system. We now show that the location of human-α-Syn in glutamatergic neurones is synaptic, and that it is enriched in crude synaptic preparations from the brain of L62 mice. Importantly, we confirm that this elevation in synaptic human-α-Syn is normalised by treatment with HMTM. The results confirm, therefore, that HMTM acts as an inhibitor of synuclein aggregation in the brain and decreases the synaptic load of pathology.

Given the possibility to both induce and reverse synaptic human-α-Syn pathology in L62 mice, we investigated how these changes impact on a range of structural synaptic proteins and glutamatergic receptor proteins. Surprisingly, the levels of structural synaptic proteins examined (synapsin, VAMP2, synaptophysin and SNAP25) were unaffected by human-α-Syn aggregation and/or HMTM administration. Exceptions are the presynaptic SNARE protein syntxin and the post-synaptic protein PSD-95 that are increased in L62 mice only when HMTM was given. This drug sensitivity in a subset of synaptic proteins suggests a decline in synaptic function rather than synapse loss and is in line with findings from the striatum of transgenic mice overexpressing a truncated human α-Syn (1–120) [45]. Synaptic accumulation of α-Syn was accompanied by an age-dependent redistribution of SNARE proteins SNAP-25, syntxin-1 and VAMP-2, but no synapse loss [45]. Similarly, syntxin-1A and VAMP-2 but not SNAP-25 were significantly reduced in extracellular vesicles from peripheral blood from PD subjects compared to controls [46]. Less relevant, but indicative of a similar mechanism, are data from a proteomic study on CSF from AD patients which confirmed increased amounts of syntxin-1, and VAMP-2 [47], while others reported that syntxin, SNAP-25 and synuclein showed a biphasic abundance rather than a static decrease/increase in AD brains in response to Braak staging [48]. These data support the idea that remodelling of synaptic proteins is an early response to pathological protein formation in multiple diseases and this process is truthfully mimicked in L62. This is consistent with adaptations in the post-synapse, here measured as altered PSD-95/glutamate receptors, possibly as an indirect response to presynaptic changes in protein expression.

As with the structural synaptic proteins, the levels of most glutamatergic receptor proteins were unaffected by human-α-Syn aggregation. The main exception was a selective increase in mGluR5 in L62 mice, and the reversal of this effect by HMTM treatment. Similarly, HMTM treatment reduced the levels of the phosphorylated AMPA subunit of GluA2. There is normally a negative correlation between the NMDA subunits (GluN1 and GluN2A) that was absent in L62 mice, and treatment with HMTM normalised the ratio of these subunits although it did not re-establish the correlation. Alterations in mGluR5 receptor expression and function have been widely reported in α-Syn over-expressing models [92] and it appears to be a specific and crucial step for the induction and progression of α-Syn-mediated pathology and microglia-associated neuroinflammation [93]. The correction of mGluR5 levels by HMTM therefore constitutes a further beneficial action of the drug. This feature in our model corroborates observations in PET brain images from PD patients also showing heightened mGluR5 levels [84] and suggests that PD patients may be at risk of hyperexcitation and that downregulation of calcium-activating glutamate channels including mGluR5 and NMDA – both are achieved by HMTM administration - is a valid treatment strategy to prevent excitotoxicity.

The mechanism for this selectivity of adaptations for mGluR5 and GluN1/2 remains to be defined. Others have suggested that a differential distribution of mGluRs and NMDA receptor subunits in the brain and their compartmentalisation at the synaptic junction e.g., cell-surface vs. extracellular compartment must be considered to understand the selective changes in PD (for review see [49]).

The effects of protein aggregation on synaptic protein levels are limited in L62 mice, we investigated how their relationships are affected using a pairwise correlation analysis approach. The fine-tuning of the synaptic machinery is needed for proper synaptic functioning and small changes may lead to the synaptic pathology that is often observed in neurodegenerative disorders [50]. Comparison of the significant pairwise correlations seen in wild-type and L62 mice revealed the loss of normal correlations and the emergence of several novel possibly pathological correlations. Notably, there was an almost...
complete loss of correlations for PSD-95, a stabilizer for NMDA receptors [43], and other glutamate receptor proteins. These were replaced in L62 mice by abnormal glutamate receptor correlations: GluN2A & GluA4, GluA1 & GluA4, GluA1 & GluN1, and GluA2 & PSD-95. This is the first analysis of this kind published to date and so it is not possible to make comparisons with other reports. However, the importance of differential expression levels and putative correlations of NMDA receptor subtypes has been confirmed for multiple brain regions, diseases, and behavioural responses [51–53]. In our specific analysis, the emergence of novel correlations is most likely an adaptation to the overexpression of human-α-Syn and the progressive accumulation of its aggregated species. Indeed, this causal relationship is underlined by the fact that α-Syn aggregation is inhibited by HMTM and reduced these pathological correlations.

Having shown that human-α-Syn pathology induces a range of abnormalities in glutamatergic proteins and that these can be partially corrected by treatment with HMTM, we investigated how these respond to pharmacological manipulations using two well established glutamatergic antagonists, MTEP and memantine. It may be argued that lower receptor levels (mGLUR5) are functionally more sensitive to blockade so that drug-induced effects become stronger. However, no difference between genotypes was observed upon treatment with the mGLUR5 antagonist MTEP. Here, MTEP was administered acutely to induce a behavioural readout. This contrasts with the commonly held perception that longer-term treatment with mGLUR5 antagonists (e.g. ADX-48621; AFQ-056) may be therapeutically exploited in PD patients with levodopa-induced dyskinesia [54]. That no difference was observed for MTEP is consistent with the observations following NMDA blockade using memantine in the light/dark box. In this case, there was no effect of memantine on anxiety and locomotion in wild-type or in L62 mice, and no difference between them. While this argues for an insensitivity of the test for memantine, at least at the doses given in this study, we had hypothesised that long term administration of memantine in drinking water at doses that produced steady-state mouse plasma levels that are clinically relevant [39] might be able to reduce α-Syn induced functional changes [55]. Although we previously have reported an anxiety phenotype in L62 mice [44], this was not reproduced here possibly due to the use of mice at a younger age. Older mice did not present with a robust anxiety phenotype in the elevated plus maze [30] suggesting technical differences and age-dependent disease progression are important considerations when working with L62 mice. Overall, the abnormalities in glutamatergic receptor expression demonstrated for L62 mice did not affect the response pattern to MTEP or memantine, although the receptor changes were clearly linked to the overexpression of α-Syn. Consequently, the lowering of both NMDA and mGLUR5 receptors may be too small for induction of behavioural consequences. Consistent with a lack of post-synaptic change in glutamate functioning in L62, selective alterations of presynaptic transmitter release-mediated proteins were also not effective for induction of a hyperglutamatergic state as shown by others [56]. The use of older mice with more advanced pathology, different pharmacological tools, their combined administration, or wider dose ranges in conjunction with the application of more challenging behavioural/physiological paradigms remain to be tested to further explore these functional glutamatergic deficits.

5. Conclusions

We have demonstrated that transgenic human-α-Syn accumulates in glutamatergic synapses, and that it is able to induce a number of abnormalities in both structural and glutamate receptor proteins, both in terms of their levels and their correlations with one another. These changes were insufficient to produce corresponding differences in behavioural responses to two glutamatergic antagonists, unless these antagonists are able to override subtle functional abnormalities in synaptic function. We have confirmed that HMTM acts in the L62 mouse model of PD as an inhibitor of pathological aggregation of synuclein. We report also that HMTM treatment normalises both the ratio of NMDA receptor subunits and mGLUR5 levels. Our results therefore support the potential utility of HMTM as a disease-modifying treatment for PD aimed at decreasing synuclein aggregation pathology.

**Funding**

This work was funded by TauRx Therapeutics Ltd., Singapore. Z. C. was funded by the Erasmus+- programme of the European Union.

**Author contributions**

K. S., S. F., and G. R. conceptualised and designed the research. K. S. and Z. C. performed biochemical protein enrichment and immunoblotting, S. F. performed behavioural testing, M. M. performed immunohistology staining and manual cell counting, A. C. performed glutamate release studies, K. S prepared figures and conducted statistical analyses. K. S., and G. R wrote the manuscript and all authors contributed to the final text and approved it for publication.

**Data availability**

All data are provided within the manuscript or the Supporting Information.

**Declaration of Competing Interest**

C.R.H. and C.M.W. declare that they are officers in TauRx Therapeutics Ltd. K.S., C.R.H., C.M.W. and G.R. are named inventors on patent applications relating to HMTM and tau protein.

**Acknowledgements**

The authors acknowledge Dr. Dilyara Lauer and Heide Lueck for the excellent technical support with the administration of drugs, collection of brains and sectioning of brain tissue for immunohistochemistry.

**Appendix A. Supplementary data**

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcellsig.2022.110386.

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