

# Impaired Hippocampal Neuroligin-2 Function by Chronic Stress or Synthetic Peptide Treatment is Linked to Social Deficits and Increased Aggression

Michael A van der Kooij<sup>1,5</sup>, Martina Fantin<sup>1,5</sup>, Igor Kraev<sup>2</sup>, Irina Korshunova<sup>3</sup>, Jocelyn Grosse<sup>1</sup>, Olivia Zanoletti<sup>1</sup>, Ramon Guirado<sup>4,6</sup>, Clara Garcia-Mompó<sup>4</sup>, Juan Nacher<sup>4</sup>, Michael G Stewart<sup>2</sup>, Vladimir Berezin<sup>3</sup> and Carmen Sandi<sup>\*1</sup>

<sup>1</sup>Laboratory of Behavioral Genetics, Brain Mind Institute, School of Life Sciences, Ecole Polytechnique Fédérale de Lausanne EPFL, Lausanne, Switzerland; <sup>2</sup>Department of Life Sciences, The Open University, Milton Keynes, UK; <sup>3</sup>The Laboratory of Neural Plasticity, Department of Neurosciences and Pharmacology, Panum Institute, University of Copenhagen, Copenhagen, Denmark; <sup>4</sup>Cell Biology Department, Neurobiology Unit and Program in Basic and Applied Neurosciences, Universitat de València, Valencia, Spain

Neuroligins (NLGNs) are cell adhesion molecules that are important for proper synaptic formation and functioning, and are critical regulators of the balance between neural excitation/inhibition (E/I). Mutations in NLGNs have been linked to psychiatric disorders in humans involving social dysfunction and are related to similar abnormalities in animal models. Chronic stress increases the likelihood for affective disorders and has been shown to induce changes in neural structure and function in different brain regions, with the hippocampus being highly vulnerable to stress. Previous studies have shown evidence of chronic stress-induced changes in the neural E/I balance in the hippocampus. Therefore, we hypothesized that chronic restraint stress would lead to reduced hippocampal NLGN-2 levels, in association with alterations in social behavior. We found that rats submitted to chronic restraint stress in adulthood display reduced sociability and increased aggression. This occurs along with a reduction of NLGN-2, but not NLGN-1 expression (as shown with western blot, immunohistochemistry, and electron microscopy analyses), throughout the hippocampus and detectable in different layers of the CA1, CA3, and DG subfields. Furthermore, using synthetic peptides that comprise sequences in either NLGN-1 (neurolide-1) or NLGN-2 (neurolide-2) involved in the interaction with their presynaptic partner neurexin (NRXN)-1, intra-hippocampal administration of neurolide-2 led also to reduced sociability and increased aggression. These results highlight hippocampal NLGN-2 as a key molecular substrate regulating social behaviors and underscore NLGNs as promising targets for the development of novel drugs for the treatment of dysfunctional social behaviors.

*Neuropsychopharmacology* (2014) **39**, 1148–1158; doi:10.1038/npp.2013.315; published online 11 December 2013

**Keywords:** aggression; chronic restraint stress; hippocampus; neuroligin; sociability

## INTRODUCTION

Substantial evidence highlights the synaptic cell adhesion molecules neuroligins (NLGNs) and neurexins (NRXNs) as critical regulators of the neural excitation/inhibition (E/I) balance (Levinson and El-Husseini, 2005; Südhof, 2008). The trans-synaptic complex formed by postsynaptically

expressed NLGNs with their presynaptic partners, NRXNs, has been critically implicated in the maintenance and function of excitatory glutamatergic and inhibitory gamma-aminobutyric acid (GABA)-ergic synapses (Südhof, 2008). Among the four members of the NLGN family, NLGN-1 and NLGN-2 are typically associated with either excitatory (NLGN-1) or inhibitory (NLGN-2) synapses (Graf *et al*, 2004; Chih *et al*, 2005).

Alterations in the balance between neural E/I have been proposed to underlie behavioral dysfunctions in several psychiatric disorders, such as schizophrenia and autism spectrum disorders, characterized by marked deficits in social interactions and communication (Harrison and Weinberger, 2005; Südhof, 2008). This view is supported by clinical evidence reporting mutations in genes encoding for NLGN and NRXNs (Sun *et al*, 2011; Gauthier *et al*, 2011). Furthermore, mice exhibiting mutations in NLGNs were shown to display alterations in the E/I balance as well as

\*Correspondence: Dr C Sandi, Laboratory of Behavioral Genetics, Brain Mind Institute, School of Life Sciences, Ecole Polytechnique Fédérale de Lausanne EPFL, Swiss Federal Institute of Technology, Station 15—ABB 115, Lausanne CH-1015, Switzerland, Tel: +41 0 21 693 9534, Fax: +41 0 21 693 9636, E-mail: carmen.sandi@epfl.ch

<sup>5</sup>These authors contributed equally to this work.

<sup>6</sup>Current address: Neuroscience Center, University of Helsinki, Helsinki 00790, Finland.

Received 17 July 2013; revised 20 September 2013; accepted 31 October 2013; accepted article preview 11 November 2013

abnormal social behaviors (Tabuchi *et al*, 2007; Hines *et al*, 2008; Jamain *et al*, 2008; Blundell *et al*, 2010).

This genetic evidence is in line with the hypothesis that pathological social behaviors can emerge from the disruption in the E/I balance occurring in relevant neural circuits during critical periods of development (Gogolla *et al*, 2009). However, a recent report (Yizhar *et al*, 2011) showed that the acute alteration of this balance in adulthood can also have immediate effects: the acute elevation of the E/I balance in the prefrontal cortex in mice, by optogenetic facilitation of glutamatergic activity, was shown to reduce social exploration (Yizhar *et al*, 2011). These findings raise the possibility that not only genetic factors, but also life experiences or treatments alter the expression and/or function of key molecular pathways that control the levels of excitatory and/or inhibitory synapses. These changes could underlie alterations in social behaviors occurring in adulthood.

In rodents, chronic stress is possibly the best characterized example of environmentally induced social avoidance (Toth and Neumann, 2013), and emerging evidence indicates that it can also increase aggressive behavior (Wood *et al*, 2008). Chronic stress has also been shown to induce changes in neural structure and function in different brain regions, with the hippocampus being highly vulnerable to stress (McEwen, 2005). Importantly, in the hippocampus, chronic stress is thought to lead to an increase in the E/I balance as indicated by enhanced synaptic excitation (Karst and Joëls, 2003), increased levels of glutamate transporters (GLTs) (Reagan *et al*, 2004), and a reduced number of parvalbumin-immunoreactive GABAergic interneurons (Hu *et al*, 2010). A role for cell adhesion molecules in the structural and functional effects of chronic restraint stress has been substantiated in studies focusing on NCAM (and its polysialylated form, PSA-NCAM) and L1 following chronic stress (Sandi, 2004; Bisaz *et al*, 2011; Gilabert-Juan *et al*, 2011). We selected the 3-week chronic restraint stress paradigm in rats, as it has been shown to increase aggressive behavior against homecage mates (Wood *et al*, 2003, 2008), as well as for its well-characterized effects in the literature at different levels of analysis, including morphological, electrophysiological, and molecular levels, particularly with regards to the hippocampus (Pavlidis *et al*, 2002; Stewart *et al*, 2005; Donohue *et al*, 2006; McEwen, 2012).

In this study, we aimed to investigate whether chronic stress would lead to changes in the expression levels of NLGN-1 and NLGN-2 in specific hippocampal subfields in association with alterations in social behavior (sociability and aggression). We hypothesized that chronic restraint stress would lead to reduced hippocampal NLGN-2 levels, with either increased or unchanged NLGN-1 levels. The hypothesis regarding NLGN-2 was based on the following observations: (i) NLGN-2-deficient mice display increased hippocampal excitability (Jedlicka *et al*, 2011) and (ii) reduced ultrasonic vocalizations (Wöhr *et al*, 2012); and (iii) hippocampus-specific overexpression of NLGN-2 led to inhibited aggressive behavior (Kohl *et al*, 2013). Regarding NLGN-1: (i) the fact that NLGN-1 overexpression leads to increased synaptic excitation in the hippocampus (Dahlhaus *et al*, 2010) led us to speculate that increased NLGN-1 expression occurs following exposure to chronic stress; however, (ii) the lack of evidence for alterations in

sociability or aggressive behaviors from genetic studies manipulating expression levels of this gene led us to hypothesize a lack of changes in NLGN-1 expression following chronic stress. Using a combination of behavioral, biochemical, and morphological approaches, we obtained results in support of these hypotheses that led us to further postulate that pharmacological interference with NLGN-2, but not NLGN-1, function in the hippocampus would alter social and aggressive behaviors. To investigate this, we performed a follow-up pharmacological study to determine the impact of interfering with NLGN function on social behaviors through intra-hippocampal microinfusion of synthetic peptides derived from either NLGN-1 (neurolide-1) (Gjølund *et al*, 2012) or NLGN-2 (neurolide-2).

## MATERIALS AND METHODS

### Animals

Animal care procedures were conducted in accordance with the guidelines set by the European Community Council Directives (86/609/EEC) and the Cantonal Veterinary Authorities (Vaud, Switzerland). Male Sprague-Dawley rats (Charles River Laboratories; Lyon, France) weighing 250 g at the start of the experiments were pair-housed under light-(12 h light/dark cycle; lights on at 0700 hours) and temperature ( $22 \pm 2^\circ\text{C}$ )-controlled conditions. Food and water were freely available. With the exception of the resident-intruder test (performed from 0800–2000 hours), all experiments were conducted between 0830 and 1400 hours to minimize the influence of hormonal fluctuations. All animals were handled for 2 min/day for the 3 d preceding the first behavioral test or surgery. The animals used for western blot, immunohistochemistry, or electron microscopy analyses were killed 1 day after stress.

### Chronic Restraint Stress

Rats were carefully wrapped in cloth to prevent injuries from the restraint. Animals were restrained 6 h/day for 21 days in wire mesh restrainers (26 × 26 cm) in their homecage between 1000 and 1600 hours. Body weight was measured every other day during the stress protocol starting at day 1. There was no indication of wounds or injuries to the rats.

### Social Behaviors

The following tests were applied to evaluate different aspects of social behaviors: the three-chambered social approach, the resident-intruder, and the social encounter in a neutral cage tests. All behaviors were scored by a behavioral expert blinded to experimental conditions. The social approach test was performed 1 day after the stress paradigm and was performed to evaluate the animals' preference to approach a juvenile conspecific or an object (see Supplementary Materials and Methods for further details). Two weeks after the social approach, test animals were tested for aggression in the resident-intruder test. The effect of intra-hippocampal infusion of neurolide-1 and/or neurolide-2 on social behavior was assessed in the social approach test and the social encounter in a neutral cage test (see Supplementary Materials and Methods for further details).

## Western Blots

Protein analyses were performed to investigate NLGN expression in the synaptoneurosomal compartments and total homogenates from hippocampal CA1, CA3, and DG and also in the frontal cortex as control region (see Supplementary Figure S1, Supplementary Figure S2 and Supplementary Materials and Methods for further details and for validation of the NLGN-2 antibody).

## Immunohistochemistry

Immunofluorescent staining against NLGN-2 allowed for a detailed analysis of the protein in subregions of the hippocampal CA1, CA3, and DG (see Supplementary Materials and Methods for further details). We found that NLGN-2 colocalized with gephyrin that was expected, as both are expressed at GABA-ergic neurons. Furthermore, omission of the primary antibody or incubation of the primary antibody with a specific NLGN-2-blocking peptide prevented a NLGN-2 signal (Supplementary Figure S3).

## Electron Microscopy Analyses

Electron microscopy enabled us to visualize and analyze ImmunoGold-positive labeling for NLGN-2 in the hippocampus (see Supplementary Materials and Methods for further details).

## Measurement of Hippocampal Volume

Measurements of the volume of the whole hippocampus were made using the Cavalieri principle (Sousa *et al*, 1997; Popov *et al*, 2004, see Supplementary Materials and Methods for further details).

## The NLGN-Derived Peptides, Neurolide-1, and Neurolide-2

The neurolide-1 peptide (SEGNRWSNSTKGLFQRA) was previously described and validated (Gjørnlund *et al*, 2012). The neurolide-2 peptide (HSEGLFQRA) was newly developed for the current study. As no NLGN-2-derived peptide was available, we developed neurolide-2. Although there is no structural data for the NLGN-2/NRXN-1 complex, the ectodomain of NLGN-2 shares >70% sequence identity with the ectodomain of NLGN-1 (Gjørnlund *et al*, 2012), and the crystal structure of the extracellular cholinesterase-like domain from NLGN-2 has been solved (Koehnke *et al*, 2008). Thus, we designed the neurolide-2 peptide based on sequence and structure homology between homologs sequence motifs in NLGN-2 and NLGN-1, respectively (Figure 4a–c), assuming that if the neurolide-1 motif is involved in NLGN-1 interaction with NRXN-1 $\beta$  (Gjørnlund *et al*, 2012), so it might be the neurolide-2 motif. The difference between these two motifs is that neurolide-1 includes a sequence corresponding to splice site B in NLGN-1, which increases affinity of the protein to NRXN-1 $\beta$  binding. Splice site B is absent in NLGN-2. Thus, the difference between the sequences of neurolide-2 and neurolide-1 reflects the fundamental difference in structural

(and therefore functional) modifications between NLGN-2 and NLGN-1.

The neurolide-2 peptide (HSEGLFQRA) was synthesized as a tetramer composed of four monomers coupled to a lysine backbone. Scrambled versions (FRGEASLQH, QAS-FELRHG, and FEASHRLQG) and reversed form (ARQFL-GESH) of 2NLGN2d peptide were synthesized in the same way by Schafer-N (Copenhagen, Denmark). The peptides were synthesized using the solid-phase Fmoc protection strategy, and purity was estimated to be  $\geq 80\%$  by high-performance liquid chromatography. The peptides were reconstituted in sterile distilled water, and the concentrations were determined by measuring the absorbance at 205 nm. Human recombinant NLGN-2 was obtained from R&D Systems (Abingdon, UK).

The concentration for the *in vitro* assay for neurite outgrowth and for the *in vivo* microinfusion experiments were selected based on a cell survival assay (see Supplementary Materials and Methods for further details on neurolide-1, as well as Supplementary Figure S4).

## Neurite Outgrowth

Hippocampal neurons were obtained on embryonic day 19 from Wistar rat embryos (Charles River Laboratories, Kisselegg, Germany) as described previously (Kraev *et al*, 2011). Neurite outgrowth was determined as previously described (Kolkova *et al*, 2000) (see Supplementary Materials and Methods for further details).

## Plasma Corticosterone Analyses

Plasma samples (dilution 1/40) were assayed by a commercially available enzyme-linked immunoabsorbent assay (Corticosterone EIA Kit, Enzo Life Sciences, Lausen, Switzerland). The intra-assay coefficient of variation was 8% and 6.6% for low- and high concentrations, respectively. The inter-assay coefficient of variation was 13.1% and 7.8% for low- and high concentrations, respectively.

## Surgery and Pharmacological Infusions

Rats subjected to pharmacological experiments were bilaterally implanted with 5-mm stainless steel guide cannulae (Plastics One, Roanoke, VA, USA) aimed at the dorsal hippocampus. Bilateral simultaneous microinfusions of either the NLGN-1-derived peptide, termed neurolide-1 (Gjørnlund *et al*, 2012), or the NLGN-2-derived peptide, termed neurolide-2 (dose for each peptide: 2.5  $\mu\text{g}$  in 1  $\mu\text{l}$  vehicle) were delivered at 0.5  $\mu\text{l}/\text{min}$  over 2 min. The injector remained in place for 1 min additionally to allow local drug diffusion. Animals were infused once per day over 5 consecutive days before behavioral experiments. Thereafter, animals were killed by i.p. pentobarbital injection, and correct cannulae placement was verified with Evans blue and histology (see Supplementary Materials and Methods for further details).

## Open-Field and Morris Water Maze

To investigate the specificity of intra-hippocampal neurolide-2 infusion on social behaviors, we assessed animals'

behavior after neurolide-2 infusion in the open-field (anxiety and locomotion) and Morris water maze (cognitive integrity). For methodological details see Supplementary Materials and Methods.

### Statistical Analysis

Data are expressed as the mean  $\pm$  SE. Behavioral observations from the social approach test and corticosterone data were analyzed using a two-way repeated measures (RM) analysis of variance (ANOVA) (Yang *et al*, 2011) followed by Bonferroni *post hoc* tests where appropriate. The *in vitro* data were analyzed using one-way RM ANOVA followed by the Bonferroni *post hoc* tests where appropriate. Two-sample comparisons were analyzed using the two-tailed Student's *t*-test. Data were considered statistically significant when  $p < 0.05$ .

## RESULTS

### Chronic Stress Reduces Social Investigation and Increases Aggressive Behavior

Body weight gain was reduced by chronic stress (data not shown), confirming the stressful nature of the restraint protocol. In addition, stress affected exploration in the social approach task (two-way RM ANOVA, main effect of stress  $F_{1,26} = 7.35$ ,  $p = 0.01$ , controls:  $n = 15$ , stressed:  $n = 13$ , Figure 1a). *Post hoc* tests showed that stress reduced investigation of the juvenile ( $t = 4.16$ ,  $p < 0.001$ ) but not the object ( $t = 0.31$ ,  $p > 0.05$ ). Locomotor activity did not differ between controls and stressed animals (Figure 1b;  $t = 0.94$ ,  $df = 25$ ,  $p = 0.36$ ). The same rats were tested in the resident-intruder test 14 days afterwards. Resident rats that had experienced chronic stress were overly aggressive against their matched intruder as compared with control residents (Figure 1c;  $t = 2.43$ ,  $df = 25$ ,  $p = 0.02$ ). The enhanced aggression exhibited by stressed animals is reflected by the components that comprise total offensive behavior (Figure 1d–f; offensive upright:  $t = 2.88$ ,  $df = 25$ ,  $p = 0.008$ ; keeping down:  $t = 2.27$ ,  $df = 25$ ,  $p = 0.03$ ; and a nonsignificant tendency for lateral threat:  $t = 1.59$ ,  $df = 25$ ,  $p = 0.12$ ). Moreover, stressed rats tended to bite their opponent more often than controls (Figure 1g; control:  $2.8 \pm 1.0$ ; stressed:  $5.7 \pm 1.2$ ;  $t = 1.88$ ,  $df = 25$ ,  $p = 0.07$ ).

### Chronic Stress Leads to Decreased Expression of NLGN-2 Throughout the Hippocampus

Western blot analyses from synaptoneurosomal fractions indicated a reduction in NLGN-2, but not NLGN-1, protein levels throughout the different hippocampal subfields CA1 (NLGN-1:  $t = 0.92$ ,  $df = 10$ ,  $p = 0.38$ ,  $n = 6$ /group, Figure 2a; NLGN-2:  $t = 2.48$ ,  $df = 10$ ,  $p = 0.03$ ,  $n = 6$ /group, Figure 2e), CA3 (NLGN-1:  $t = 0.67$ ,  $df = 9$ ,  $p = 0.52$ , control:  $n = 5$ , stress:  $n = 6$ , Figure 2b; NLGN-2:  $t = 2.48$ ,  $df = 9$ ,  $p = 0.035$ , control:  $n = 6$ , stress:  $n = 5$ , Figure 2f) and DG (NLGN-1:  $t = 0.08$ ,  $df = 16$ ,  $p = 0.94$ ,  $n = 9$ /group, Figure 2c; NLGN-2:  $t = 3.34$ ,  $df = 10$ ,  $p = 0.007$ ,  $n = 6$ /group, Figure 2g). The chronic stress-induced downregulation of NLGN-2 was specific to the hippocampus, as we found that stress did not affect expression of NLGN-2 (or NLGN-1) in the frontal

cortex (NLGN-1:  $t = 0.45$ ,  $df = 9$ ,  $p = 0.67$ , control:  $n = 6$ , stress:  $n = 5$ , Figure 2d; NLGN-2:  $t = 0.81$ ,  $df = 10$ ,  $p = 0.44$ ,  $n = 6$ /group, Figure 2h). Furthermore, expression levels of NLGN-1 and NLGN-2 in the total fraction from hippocampus or frontal cortex were not affected by stress (Supplementary Figure S2). Validation of the NLGN-2 antibody for the western blot and immunohistochemical analyses is presented in Supplementary Figure S1 and S3.

Reduced levels of hippocampal NLGN-2 in chronic stress-treated animals were confirmed by immunohistochemistry as described below. We found reduced NLGN-2 expression in different layers throughout the CA1 (stratum oriens,  $t = 1.04$ ,  $df = 6$ ,  $p = 0.34$ ; stratum pyramidale:  $t = 0.57$ ,  $df = 6$ ,  $p = 0.59$ , stratum radiatum,  $t = 2.46$ ,  $df = 6$ ,  $p = 0.049$ ; stratum lacunosum-moleculare:  $t = 2.84$ ,  $df = 6$ ,  $p = 0.03$ , Figure 3a), CA3 (stratum oriens,  $t = 3.12$ ,  $df = 6$ ,  $p = 0.02$ ; stratum pyramidale:  $t = 2.64$ ,  $df = 6$ ,  $p = 0.04$ ; stratum radiatum:  $t = 2.63$ ,  $df = 6$ ,  $p = 0.04$ ; stratum lacunosum-moleculare:  $t = 1.60$ ,  $df = 6$ ,  $p = 0.16$ , Figure 3b), and DG (granular cell layer:  $t = 2.81$ ,  $df = 6$ ,  $p = 0.03$ ; molecular cell layer:  $t = 2.32$ ,  $df = 6$ ,  $p = 0.06$ , Figure 3c).

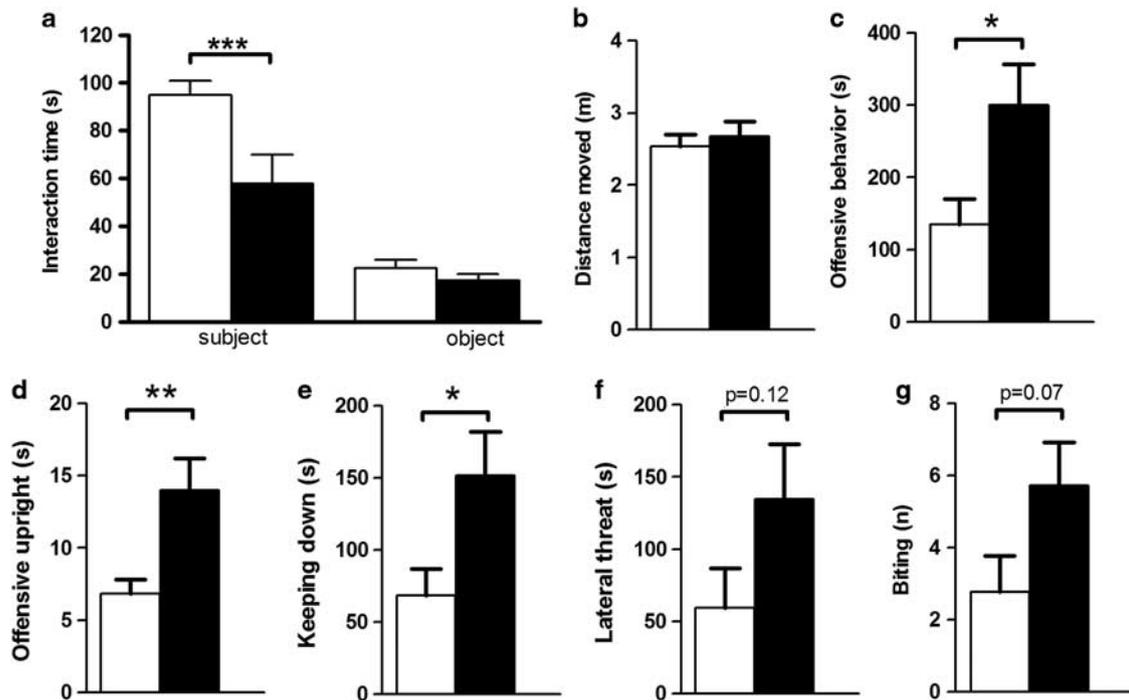
Using electron microscopy, we were able to confirm that the density of total hippocampal NLGN-2 was reduced in stressed animals as compared with controls ( $t = 2.52$ ,  $df = 6$ ,  $p = 0.045$ , Figure 3d). An example of ImmunoGold-labeled particles for NLGN-2 is shown at an inhibitory synapse (Figure 3e). We found that total hippocampal volume was not affected by stress ( $t = 0.48$ ,  $df = 14$ ,  $p = 0.64$ , Figure 3f).

### *In Vitro* Characterization of the NLGN-2-Derived Peptide: Effects on Neurite Outgrowth

As the only existing and characterizing peptide was neurolide-1 peptide (Gjølund *et al*, 2012), we developed here the neurolide-2 peptide based on sequence and structure homology between homologs sequence motifs in NLGN-2 and NLGN-1, respectively (Figure 4a–c). For its validation, we first performed an *in vitro* study in primary hippocampal cell cultures to check different peptide concentrations in cell survival (see Supplementary Materials and Methods and Supplementary Figure S4). We, then, proceeded to assess the effect of neurolide-2 in neurite outgrowth in hippocampal neurons. A treatment effect on neurite outgrowth was observed (one-way RM ANOVA,  $p < 0.0001$ ) only with neurolide-2 ( $t = 4.36$ ,  $p < 0.01$ ; Figure 4d). The neuritogenic effect of neurolide-2, as well as of the whole NLGN-2 ectodomain, was abrogated by knocking down NRXN-1 $\beta$  (Figure 4e–f), indicating that in single-neuronal cultures, neuritogenic activity of the peptide required NRXN-1 $\beta$  expression, and that the neurolide-2 peptide might have a potential to interfere with NLGN-2-NRXN-1 $\beta$  binding. This result shows that the peptide is biologically active and, accordingly, potentially effective to disrupt NLGN-2-NRXN-1 $\beta$  interactions.

### Infusion of a NLGN-2-, but not NLGN-1-, Derived Peptide into the Hippocampus Leads to Reduced Social Investigation and Increased Aggression

First, we found that infusion of neurolide-1 in the hippocampus did not affect social investigation (two-way



**Figure 1** Effects of chronic restraint stress on sociability and aggressive behavior. Investigatory behavior for a juvenile and an object (\*\* $p < 0.001$ , controls:  $n = 15$ , stressed:  $n = 13$ ) (a). Locomotor activity during the social approach task (b). Total aggressive behavior expressed in the resident–intruder test (\* $p < 0.05$ ) (c); offensive upright (\*\* $p < 0.01$ ) (d); keeping down (\* $p < 0.05$ ) (e); lateral threat (f) and biting (g). White bars indicate controls whereas the black bars indicate stressed animals. Error bars represent SEM.

RM ANOVA, main treatment effect,  $F_{1,10} = 0.02$ ,  $p = 0.88$ ,  $n = 6$ /group, Figure 5a). However, neurolide-2 infusion did reduce social investigation as compared with vehicle-treated animals (two-way RM ANOVA, main treatment effect,  $F_{1,17} = 4.65$ ,  $p = 0.046$ . *post hoc* tests:  $p < 0.01$ , vehicle:  $n = 6$  and neurolide-2:  $n = 7$ , Figure 5b). None of the peptides affected overall locomotor activity (neurolide-1:  $t = 0.55$ ,  $df = 12$ ,  $p = 0.59$ ,  $n = 7$  and neurolide-2:  $t = 0.53$ ,  $df = 10$ ,  $p = 0.61$ ,  $n = 6$ , Figure 5c).

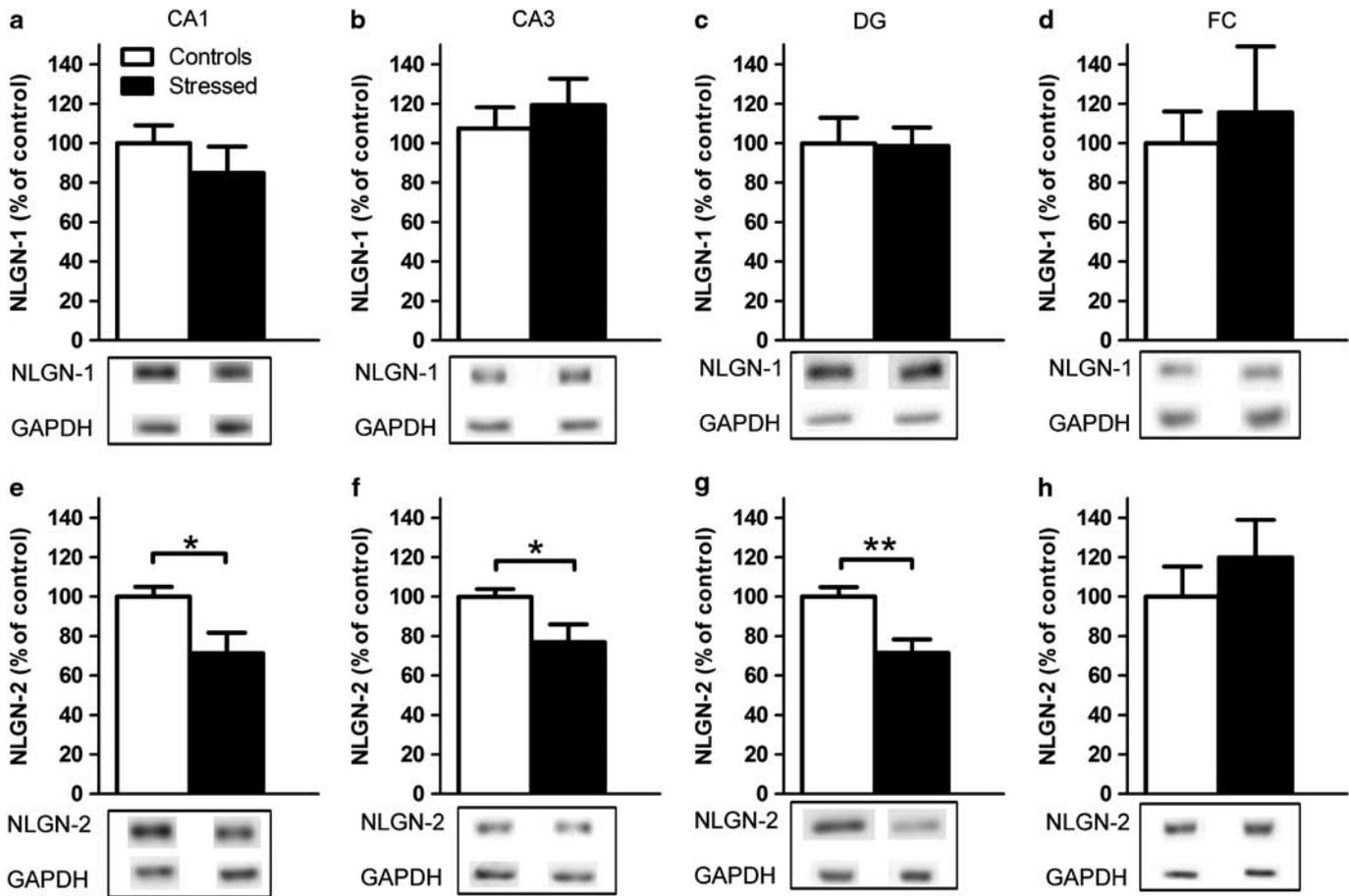
Neurolide-2 treatment led to increased aggressive behavior when animals ( $n = 7$ /group) were exposed to an unfamiliar male in a neutral cage ( $t = 2.66$ ,  $df = 12$ ,  $p = 0.02$ , Figure 5d). In line with the results on stressed animals in the resident–intruder task, animals treated with neurolide-2 tended to show increased amounts of offensive upright ( $t = 1.70$ ,  $df = 12$ ,  $p = 0.12$ , Figure 5e), keeping down ( $t = 2.17$ ,  $df = 12$ ,  $p = 0.05$ , Figure 5f), although the duration of lateral threat was low and not different between the two groups ( $t = 0.28$ ,  $df = 12$ ,  $p = 0.78$ , Figure 5g). The infusion of neurolide-2 into the hippocampus did not affect peripheral corticosterone levels either at baseline or immediate after the social encounter (two-way RM ANOVA, main effect of social encounter,  $F_{1,39} = 42.6$ ,  $p < 0.001$ , but no effect of drug,  $F_{1,39} = 0$ ,  $p = 0.97$ ,  $n = 13$  for vehicle/homecage and  $n = 10$  for all other groups, Figure 5h). Importantly, the effectiveness of neurolide-2 hippocampal treatment seems to be quite specific for social behaviors, as in the open field we found that locomotor activity or anxiety-like behavior were unaffected (locomotor activity:  $t = 0.44$ ,  $df = 11$ ,  $p = 0.67$  and anxiety-like behavior:  $t = 1.49$ ,  $df = 11$ ,  $p = 0.16$ , vehicle:  $n = 6$ , neurolide-2:  $n = 7$ ) (see Supplementary Figure S5). Moreover, spatial learning in the

water maze was also not affected by neurolide-2 infusion (Supplementary Figure S6).

## DISCUSSION

This study shows that chronic restraint stress in adult rats leads to reduced sociability and increased aggression along with a reduction of NLGN-2, but not NLGN-1, expression throughout the hippocampus that was detectable in different layers of the CA1, CA3, and DG subfields. The decrease in NLGN-2 was specific to the synaptoneurosomal compartment, as NLGN-2 protein levels were not affected in the total fraction. These results led us to speculate that interfering with NLGN-2 function in the hippocampus of adult rats would affect social behaviors.

Using synthetic peptides that comprise sequences in either NLGN-1 (neurolide-1) or NLGN-2 (neurolide-2) involved in the interaction with their presynaptic partner NRXN-1 (Gjørslund *et al*, 2012), we found that intra-hippocampal administration (over 5 consecutive days) of neurolide-2 in adult rats reduced sociability and increased aggression. Together with our previous findings showing that viral-induced overexpression of NLGN-2 in the adult hippocampus leads to decreased aggression (Kohl *et al*, 2013), these results highlight hippocampal NLGN-2 as a key molecular substrate regulating social behaviors. In an earlier study, however, constitutive NLGN-2 knockout mice did not differ from controls in social interactions (Blundell *et al*, 2009). We suspect that during development, compensatory mechanisms are at work in the NLGN-2



**Figure 2** Effects of chronic restraint stress on hippocampal protein neuroligin-1 (NLGN-1) and neuroligin-2 (NLGN-2) expression. Synaptoneurosomal protein fractions of NLGN-1 (a–d) and NLGN-2 (e–h) in the hippocampal CA1 (a and e), ( $n = 6/\text{group}$ ); CA3 (b and f), ( $n = 5\text{--}6/\text{group}$ ); dentate gyrus (c and g), ( $n = 9/\text{group}$ ); and in the frontal cortex (d and h), ( $n = 5\text{--}6/\text{group}$ ) (\* $p < 0.05$ , \*\* $p < 0.01$ ). Error bars represent SEM.

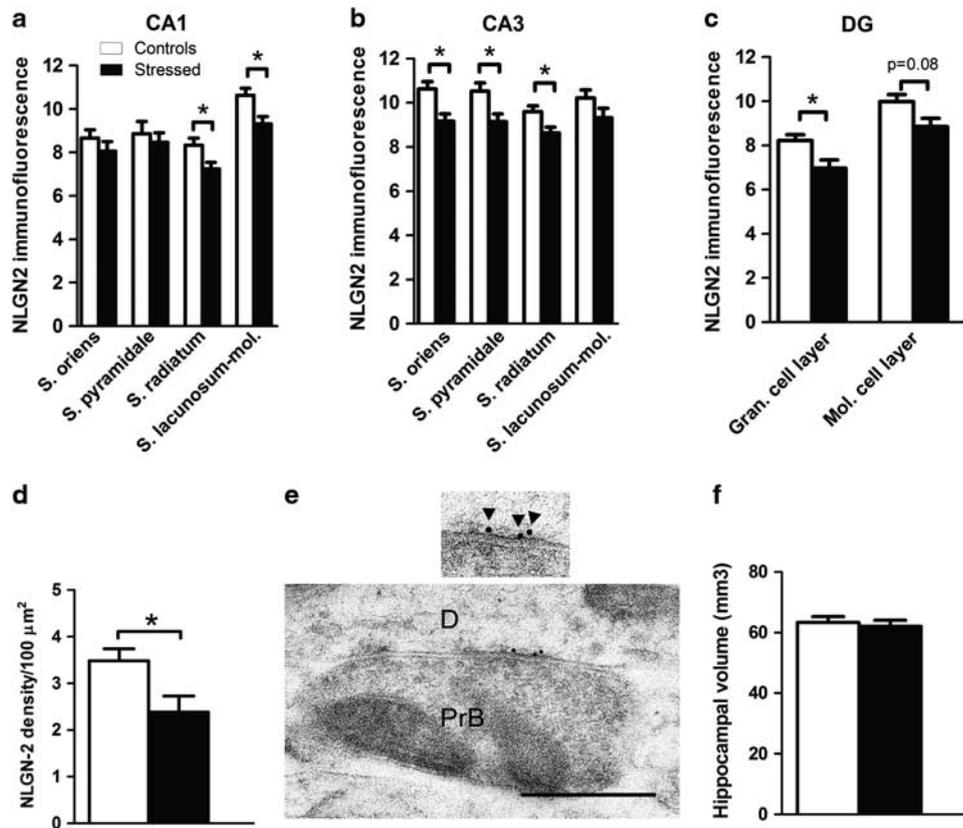
knockout mice that may have masked the expression of the social impairments in these animals.

The reduction in social exploration observed following exposure to chronic stress was not because of a general decrease in locomotor activity, which is in agreement with the literature (Kleen *et al*, 2006). These results are in line with the finding of social avoidance in rats exposed to a mild chronic stress protocol of the same length as here (21 days) (Kompagne *et al*, 2008) and with mounting evidence indicating reduced sociability following sustained exposure to stress (Toth and Neumann, 2013). The increased aggression that we find in stressed animals in a resident–intruder test extends previous reports, indicating increased aggression toward homecage mates (Wood *et al*, 2008).

The mechanisms whereby chronic restraint stress alters individuals' social interactions are probably multiple. Chronic restraint stress is known to induce neural remodeling in several brain regions, notably including the hippocampus, but also the prefrontal cortex and amygdala (Leuner and Shors, 2012; McEwen, 2012). A growing body of evidence suggests that the hippocampus is critically involved in the regulation of social interactions (Kogan *et al*, 2000; Uekita and Okanoya, 2011) and aggressive behaviors (Maaswinkel *et al*, 1997; Uekita and Okanoya,

2011). In agreement with the literature (Lee *et al*, 2009), we found evidence for a marginal (2.2%), and nonsignificant reduction in hippocampal volume in chronically stressed rats. Importantly, chronic stress is known to induce neural remodeling, including dendritic atrophy and changes in synaptic morphology, throughout the hippocampus (Sousa *et al*, 2000; Bessa *et al*, 2009; Stewart *et al*, 2005; Donohue *et al*, 2006; McEwen, 2012).

Substantial evidence highlights changes in the neural circuit E/I balance as an underlying mechanism for social dysfunction (Harrison and Weinberger, 2005; Südhof, 2008). Importantly, different lines of evidence indicate that chronic stress might lead to an increase in the E/I balance in the hippocampus. In particular, chronic stress was shown (i) to enhance glutamate transmission and synaptic excitation in different hippocampal subfields (Karst and Joëls, 2003; Joëls *et al*, 2004); (ii) to increase expression levels of the GLTs-1 and -1b (Reagan *et al*, 2004) and synaptobrevin/vesicle-associated membrane protein 2, a synaptic vesicle molecule involved in neurotransmitter— notably glutamate—release (Gao *et al*, 2006); and (iii) chronic stress was also shown to lead to a reduction in extracellular GABA levels (Grønli *et al*, 2007), as well as in the number of parvalbumin-immunoreactive GABA-ergic interneurons (Hu *et al*, 2010).



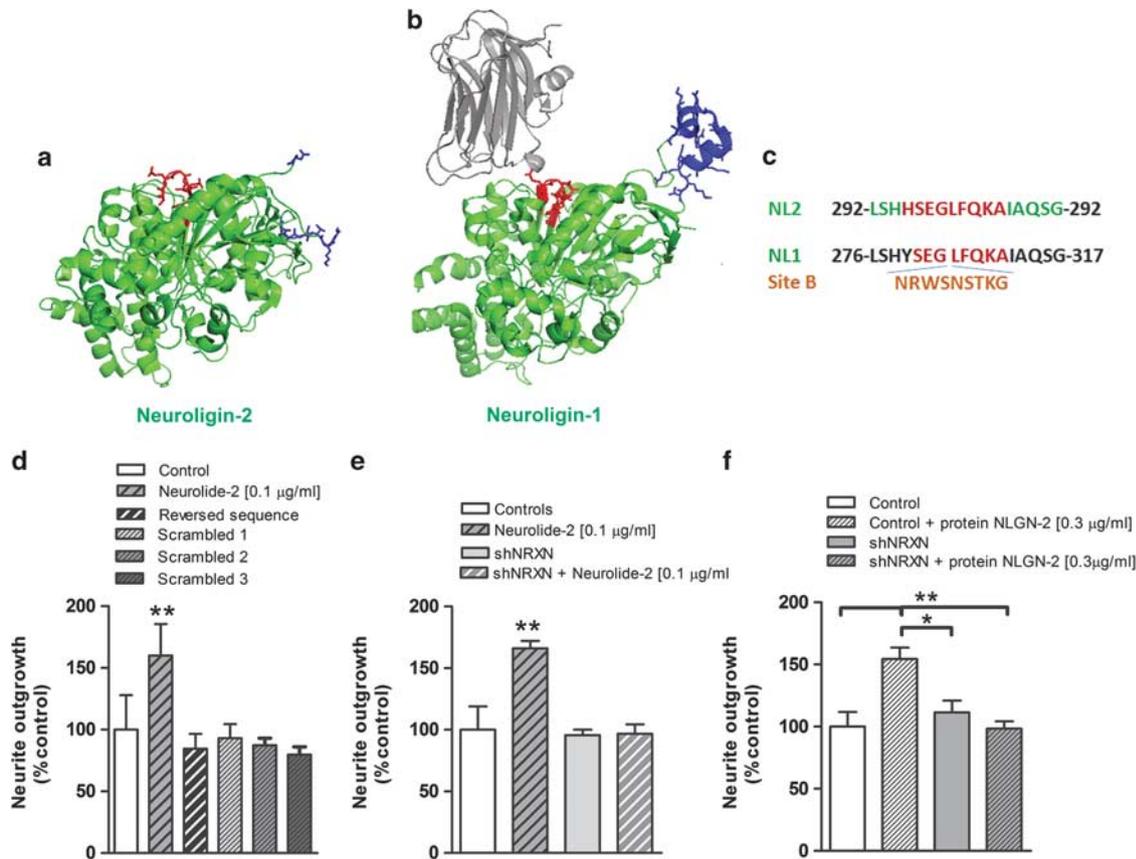
**Figure 3** Effects of chronic restraint stress on hippocampal neuroligin-2 (NLGN-2) expression in the hippocampus as revealed by immunofluorescence and electron microscopy. Immunofluorescence staining for NLGN-2 was employed to investigate the effects of chronic stress in subregions of the hippocampal CA1 (a); CA3 (b); and dentate gyrus ( $*p < 0.05$ ) (c). Hippocampal NLGN-2 density is measured by electron microscopy ( $*p < 0.05$ ) (d). ImmunoGold labeling (as indicated by arrowheads, see insert) for NLGN-2 at an inhibitory synapse (D), dendrite, PrB, presynaptic bouton, and the scale bar measures  $0.5 \mu\text{m}$ ) (e). Total hippocampal volume in controls and stressed animals (f) ( $n = 4/\text{group}$ ). Error bars represent SEM.

Altogether, these observations provide a picture of changes in the glutamatergic and GABA-ergic systems induced by chronic (restraint, in most cases) stress that, along with the electrophysiological evidence indicated above, strongly indicate a shift in the balance of the hippocampal E/I ratio toward increased excitation. Our findings showing a decreased expression of NLGN-2 throughout the hippocampus are congruent with an increased E/I ratio in stressed animals. However, given the numerous examples of stress-induced glutamatergic changes (see above), the fact that no changes were observed in the expression levels of NLGN-1 raises several questions. One possibility is that the role of this isoform in the reorganization of the glutamatergic changes induced by chronic stress occurs at earlier time points, which are not captured by this study. Alternatively, NLGN-1 might not be involved with, instead, other mechanisms being responsible. One interesting candidate is NLGN-3, as it has been implicated in both glutamatergic and GABA-ergic synapses (Budreck and Scheiffele, 2007). Non-synapse-specific mechanisms, such as the described stress-induced changes in glial glutamate transporters (Reagan *et al*, 2004), could also be involved. Nevertheless, the observed reduction in NLGN-2 expression might be sufficient to account for the described changes in the E/I balance. In support of this view is the fact that whereas the overexpression of NLGN-2 was found to

increase synaptic contacts and shifted the E/I balance downwards, overexpression of NLGN-1 did not affect these parameters (Hines *et al*, 2008).

The reduction that we find in NLGN-2 following chronic stress was detected both in synaptoneurosomes, in electron microscope images, and also in immunohistochemical preparations that revealed the widespread reduction throughout the different hippocampal subfields and layers (except for stratum oriens and stratum pyramidale in CA1 and stratum lacunosum-moleculare in CA3). Several studies have reported structural (Donohue *et al*, 2006) and molecular (Reagan *et al*, 2004; Gao *et al*, 2006) changes coinciding with the same subregions where we detect differences in NLGN-2 expression. However, it is notable that NLGN-2 was unaltered in the stratum lacunosum-moleculare of the CA3, one of the layers to which the distal apical dendritic trees of the pyramidal neurons project and where stress-induced atrophy is detected (Magariños and McEwen, 1995).

Therefore, our results illustrate that a life experience, such as chronic stress, known to elevate the hippocampal E/I ratio, leads simultaneously to a reduction in NLGN-2 expression throughout the hippocampus and to alterations in social behaviors. Yizhar *et al*, (2011) showed that elevating this ratio in the prefrontal cortex can induce immediate deficits in sociability. Importantly, our

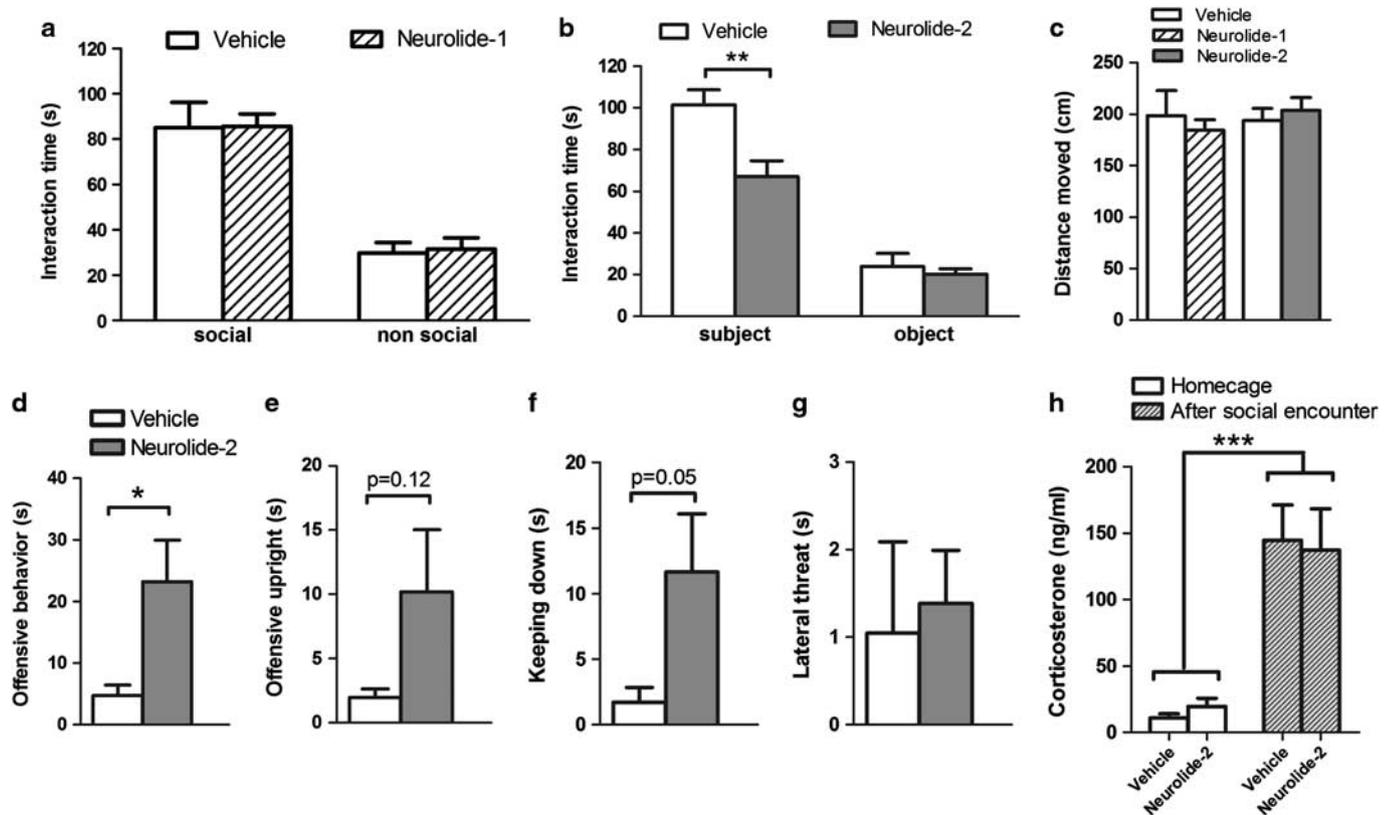


**Figure 4** Design of Neurolide-2, a neuroligin-2 (NLGN-2)-derived peptide. Model of NLGN-2 (PDB identification 3BL8) (a). Localization of the neurolide-2 sequence motif is shown in red. Localization of splice site A is shown in blue. (b) Model of the NLGN-1 (green)/neurexin (NRXN)-1 $\beta$  (gray) complex (PDB identification 3VKF). Localization of part of the neurolide-1 sequence motif (without splice site B) is shown in red. Localization of splice site A is shown in blue. (c) Sequence motif of neurolide-2 is shown in red (top, UniProtKB/Swiss-Prot identification Q69ZK9). Sequence motif of neurolide-1 (bottom, UniProtKB/Swiss-Prot identification Q62765) is shown in red. It includes splice site B (brown). The *in vitro* effects of neurolide-2 on neurite outgrowth as compared with the reversed, or a scrambled sequence (d). Shown is the effect of neurexin (NRXN)-knockdown on neurolide-2- and NLGN-2 protein-induced neurite outgrowth (\* $p < 0.05$ , \*\* $p < 0.01$ ) (e and f). Error bars represent SEM.

pharmacological experiments showing that intra-hippocampal infusions of the synthetic peptide neurolide-2, but not neurolide-1, lead to similar social alterations as found following chronic restraint stress. This further supports a role for hippocampal NLGN-2 in the regulation of social behaviors (Kohl *et al*, 2013). These peptides are biologically active, as shown by their ability to stimulate neurite outgrowth in dissociated neuronal cultures, when NLGNs are not involved in trans-synaptic binding with NRXN. Our findings showing increased aggression following stress when reduced NLGN-2 expression is observed as well as following the infusion of neurolide-2, which is in fact a synthetic fragment of the NLGN-2 molecule, might appear counterintuitive. However, it is important to emphasize that the neurolide-2 peptide was designed to coincide with the exact sequence motifs in NLGN-2 that are involved in the interaction with NRXN-1 $\beta$  (see Figure 4), thus not being a full mimetic of the entire NLGN-2 protein. For example, neurolide-2 lacks critical sequences in the NLGN-2 part in interaction with the plasma membrane and intracellular compartment. As proposed for other synthetic peptides targeting specific cell adhesion molecules (Foley *et al*, 2000; Cambon *et al*, 2003; Kraev *et al*, 2011), when given *in vivo*, these peptides can disrupt

endogenous cell-cell molecular interactions and eventually display antagonistic effects. In this case, NRXN-NLGN complexes for the specific NLGNs were targeted. Therefore, our data on NLGN-2 reduction following chronic stress and neurolide-2 infusions seems to be congruent in suggesting that impaired NLGN-2 function in the hippocampus is associated with increased aggression. Importantly, we also showed here that the NLGN-derived peptides neither altered locomotor activity, anxiety-like behaviors, or spatial learning nor affected basal or activated plasma corticosterone responses, thereby excluding non-specific stress effects in the observed results on social behaviors obtained with neurolide-2.

Our study highlights for the first time NLGN-2 as a molecular target broadly affected by chronic stress exposure in the hippocampus, and suggests that impaired hippocampal NLGN-2 function might be instrumental in the development of alterations in sociability and aggression. In addition to emphasizing the role of NLGN-2 in the hippocampus (Kohl *et al*, 2013), these findings add to a growing body of data highlighting NLGN-2 in the regulation of social behaviors (Hines *et al*, 2008; Wöhr *et al*, 2012). The effectiveness of neurolide-2 to affect social behaviors underscores NLGNs as promising targets for the



**Figure 5** Effects of Neurolide-1 or Neurolide-2 infused in the dorsal hippocampus on social behavior, locomotion, and peripheral corticosterone. Investigation of a juvenile conspecific or inanimate object after treatment with neurolide-1 (a) or neurolide-2 in the dorsal hippocampus (\*\* $p < 0.01$ ;  $n = 6-7$ /group) (b). Locomotor activity during the social approach task ( $n = 6-7$ /group) (c). In a subsequent social encounter, we measured total offensive behavior (\* $p < 0.05$ ;  $n = 7$ /group) (d), offensive upright (e), keeping down (f), and lateral threat (g). Plasma corticosterone levels were taken when the animals were in their homecage and immediately after social interaction ( $n = 13$  for controls under homecage conditions and  $n = 10$  for the other groups, \*\*\* $p < 0.001$ ) (h). Error bars represent SEM.

development of novel drugs ideally capable of improving social behaviors.

## FUNDING AND DISCLOSURE

This work was supported by grants from the European Union integrated project MEMSTICK (FP7-HEALTH-F2M-2007-201600; MemStick), the Swiss National Science Foundation (310000-120791 and 31003AB-135710; Sinergia CRSIK3-122691; and the NCCR ‘The synaptic basis of mental diseases’), the Oak Foundation, the Lundbeck foundation and intramural funding from the EPFL. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

## REFERENCES

- Bessa JM, Ferreira D, Melo I, Marques F, Cerqueira JJ, Palha JA *et al* (2009). The mood-improving actions of antidepressants do not depend on neurogenesis but are associated with neuronal remodeling. *Mol Psychiatry* 14: 764–773.
- Bisaz R, Schachner M, Sandi C (2011). Causal evidence for the involvement of the neural cell adhesion molecule, NCAM, in chronic stress-induced cognitive impairments. *Hippocampus* 21: 56–71.
- Blundell J, Tabuchi K, Bolliger MF, Blaiss CA, Brose N, Liu X *et al* (2009). Increased anxiety-like behavior in mice lacking the

inhibitory synapse cell adhesion molecule neuroligin-2. *Genes Brain Behav* 8: 114–126.

- Blundell J, Blaiss CA, Etherton MR, Espinosa F, Tabuchi K, Walz C *et al* (2010). Neuroligin-1 deletion results in impaired spatial memory and increased repetitive behavior. *J Neurosci* 30: 2115–2129.
- Budreck EC, Scheiffele P (2007). Neuroligin-3 is a neuronal adhesion protein at GABAergic and glutamatergic synapses. *Eur J Neurosci* 26: 1738–1748.
- Cambon K, Venero C, Berezin V, Bock E, Sandi C (2003). Post-training administration of a synthetic peptide ligand of the neural cell adhesion molecule, C3d, attenuates long-term expression of contextual fear conditioning. *Neuroscience* 122: 183–191.
- Chih B, Engelman H, Scheiffele P (2005). Control of excitatory and inhibitory synapse formation by neuroligins. *Science* 307: 1324–1328.
- Dahlhaus R, Hines RM, Eadie BD, Kannagara TS, Hines DJ, Brown CE *et al* (2010). Overexpression of the cell adhesion molecule neuroligin-1 induces learning deficits and impairs synaptic plasticity by altering the ratio of excitation to inhibition in the hippocampus. *Hippocampus* 20: 305–322.
- Donohue HS, Gabbott PL, Davies HA, Rodríguez JJ, Cordero MI, Sandi C *et al* (2006). Chronic restraint stress induces changes in synapse morphology in stratum lacunosum-moleculare CA1 rat hippocampus: a stereological and three-dimensional ultrastructural study. *Neuroscience* 140: 597–606.
- Foley AG, Hartz BP, Gallagher HC, Rønn LC, Berezin V, Bock E *et al* (2000). A synthetic peptide ligand of neural cell adhesion molecule (NCAM) Ig1 domain prevents NCAM

- internalization and disrupts passive avoidance learning. *J Neurochem* 74: 2607–2613.
- Gao Y, Bezchlibnyk YB, Sun X, Wang JF, McEwen BS, Young LT (2006). Effects of restraint stress on the expression of proteins involved in synaptic vesicle exocytosis in the hippocampus. *Neuroscience* 141: 1139–1148.
- Gauthier J, Siddiqui TJ, Huashan P, Yokomaku D, Hamdan FF, Champagne N et al (2011). Truncating mutations in NRXN2 and NRXN1 in autism spectrum disorders and schizophrenia. *Hum Genet* 130: 563–573.
- Gilabert-Juan J, Castillo-Gomez E, Pérez-Rando M, Moltó MD, Nacher J (2011). Chronic stress induces changes in the structure of interneurons and in the expression of molecules related to neuronal structural plasticity and inhibitory neurotransmission in the amygdala of adult mice. *Exp Neurol* 232: 33–40.
- Gjørulund MD, Nielsen J, Pankratova S, Li S, Korshunova I, Bock E et al (2012). Neuroligin-1 induces neurite outgrowth through interaction with neurexin-1 $\beta$  and activation of fibroblast growth factor receptor-1. *FASEB J* 26: 4174–4186.
- Gogolla N, Leblanc JJ, Quast KB, Südhof TC, Fagiolini M, Hensch TK (2009). Common circuit defect of excitatory-inhibitory balance in mouse models of autism. *J Neurodev Disord* 1: 172–181.
- Graf ER, Zhang X, Jin SX, Linhoff MW, Craig AM (2004). Neurexins induce differentiation of GABA and glutamate postsynaptic specializations via neuroligins. *Cell* 119: 1013–1026.
- Grønli J, Fiske E, Murison R, Bjorvatn B, Sørensen E, Ursin R et al (2007). Extracellular levels of serotonin and GABA in the hippocampus after chronic mild stress in rats. A microdialysis study in an animal model of depression. *Behav Brain Res* 181: 42–51.
- Harrison PJ, Weinberger DR (2005). Schizophrenia genes, gene expression, and neuropathology: on the matter of their convergence. *Mol Psychiatry* 10: 40–68.
- Hines RM, Wu L, Hines DJ, Steenland H, Mansour S, Dahlhaus R et al (2008). Synaptic imbalance, stereotypies, and impaired social interactions in mice with altered neuroligin 2 expression. *J Neurosci* 28: 6055–6067.
- Hu W, Zhang M, Czéh B, Flügge G, Zhang W (2010). Stress impairs GABAergic network function in the hippocampus by activating nongenomic glucocorticoid receptors and affecting the integrity of the parvalbumin-expressing neuronal network. *Neuropsychopharmacology* 35: 1693–1707.
- Jamain S, Radyushkin K, Hammerschmidt K, Granon S, Boretius S, Varoqueaux F et al (2008). Reduced social interaction and ultrasonic communication in a mouse model of monogenic heritable autism. *Proc Natl Acad Sci USA* 105: 1710–1715.
- Jedlicka P, Hoon M, Papadopoulos T, Vlachos A, Winkels R, Pouloupoulos A et al (2011). Increased dentate gyrus excitability in neuroligin-2-deficient mice *in vivo*. *Cereb Cortex* 21: 357–367.
- Joëls M, Karst H, Alfarez D, Heine VM, Qin Y, van Riel E et al (2004). Effects of chronic stress on structure and cell function in rat hippocampus and hypothalamus. *Stress* 7: 221–231.
- Karst H, Joëls M (2003). Effect of chronic stress on synaptic currents in rat hippocampal dentate gyrus neurons. *J Neurophysiol* 89: 625–633.
- Kleen JK, Sitomer MT, Killeen PR, Conrad CD (2006). Chronic stress impairs spatial memory and motivation for reward without disrupting motor ability and motivation to explore. *Behav Neurosci* 120: 842–851.
- Koehnke J, Jin X, Budreck EC, Posy S, Scheiffle P, Honig B et al (2008). Crystal structure of the extracellular cholinesterase-like domain from neuroligin-2. *Proc Natl Acad Sci USA* 105: 1873–1888.
- Kogan JH, Frankland PW, Silva AJ (2000). Long-term memory underlying hippocampus-dependent social recognition in mice. *Hippocampus* 10: 47–56.
- Kohl C, Riccio O, Grosse J, Zanoletti O, Fournier C, Schmidt MV et al (2013). Hippocampal neuroligin-2 overexpression leads to reduced aggression and inhibited novelty reactivity in rats. *PLoS One* 8: e56871.
- Kolkova K, Novitskaya V, Pedersen N, Berezin V, Bock E (2000). Neural cell adhesion molecule-stimulated neurite outgrowth depends on activation of protein kinase C and the Ras-mitogen-activated protein kinase pathway. *J Neurosci* 20: 2238–2246.
- Kompagne H, Bárdos G, Szénási G, Gacsályi I, Hársing LG, Lévy G (2008). Chronic mild stress generates clear depressive but ambiguous anxiety-like behaviour in rats. *Behav Brain Res* 193: 311–314.
- Kraev I, Henneberger C, Rossetti C, Conboy L, Kohler LB, Fantin M et al (2011). A peptide mimetic targeting trans-homophilic NCAM binding sites promotes spatial learning and neural plasticity in the hippocampus. *PLoS One* 6: e23433.
- Lee T, Jarome T, Li SJ, Kim JJ, Helmstetter FJ (2009). Chronic stress selectively reduces hippocampal volume in rats: a longitudinal magnetic resonance imaging study. *Neuroreport* 20: 1554–1558.
- Leuner B, Shors TJ (2012). Stress, anxiety, and dendritic spines: What are the connections? *Neuroscience* 251: 108–119.
- Levinson JN, El-Husseini A (2005). Building excitatory and inhibitory synapses: balancing neuroligin partnerships. *Neuron* 48: 171–174.
- Maaswinkel H, Gispen WH, Spruijt BM (1997). Executive function of the hippocampus in social behavior in the rat. *Behav Neurosci* 111: 777–784.
- Magariños AM, McEwen BS (1995). Stress-induced atrophy of apical dendrites of hippocampal CA3c neurons: involvement of glucocorticoids secretion and excitatory amino acid receptors. *Neuroscience* 69: 89–98.
- McEwen BS (2005). Glucocorticoids, depression, and mood disorders: structural remodeling in the brain. *Metabolism* 54: 20–23.
- McEwen BS (2012). The ever-changing brain: cellular and molecular mechanisms for the effects of stressful experiences. *Dev Neurobiol* 72: 878–890.
- Pavlidis C, Nivón LG, McEwen BS (2002). Effects of chronic stress on hippocampal long-term potentiation. *Hippocampus* 12: 245–257.
- Popov VI, Davies HA, Rogachevsky VV, Patrushev IV, Errington ML, Gabbot PL et al (2004). Remodelling of synaptic morphology but unchanged synaptic density during late phase long-term potentiation (LTP): a serial section electron micrograph study in the dentate gyrus in the anaesthetised rat. *Neuroscience* 128: 251–262.
- Reagan LP, Rosell DR, Wood GE, Spedding M, Muñoz C, Rothstein J et al (2004). Chronic restraint stress up-regulates GLT-1 mRNA and protein expression in the rat hippocampus: reversal by tianeptine. *Proc Natl Acad Sci USA* 101: 2179–2184.
- Sandi C (2004). Stress, cognitive impairment and cell adhesion molecules. *Nat Rev Neurosci* 5: 917–930.
- Sousa N, Madeira MD, Paula-Barbosa MM (1997). Structural alterations of the hippocampal formation of adrenalectomized rats: an unbiased stereological study. *J Neurocytol* 26: 423–438.
- Sousa N, Lukoyanov NV, Madeira MD, Almeida OF, Paula-Barbosa MM (2000). Reorganization of the morphology of hippocampal neurites and synapses after stress-induced damage correlates with behavioral improvement. *Neuroscience* 97: 253–266.
- Stewart MG, Davies HA, Sandi C, Kraev IV, Rogachevsky VV, Peddie CJ et al (2005). Stress suppresses and learning induces plasticity in CA3 of rat hippocampus: a three-dimensional ultrastructural study of thorny excrescences and their postsynaptic densities. *Neuroscience* 131: 43–54.

- Südhof TC (2008). Neuroligins and neuroligins link synaptic function to cognitive disease. *Nature* **455**: 903–911.
- Sun C, Cheng MC, Qin R, Liao DL, Chen TT, Koong FJ *et al* (2011). Identification and functional characterization of rare mutations of the neuroligin-2 gene (NLGN2) associated with schizophrenia. *Hum Mol Genet* **20**: 3042–3051.
- Tabuchi K, Blundell J, Etherton MR, Hammer RE, Liu X, Powell CM *et al* (2007). A neuroligin-3 mutation implicated in autism increases inhibitory synaptic transmission in mice. *Science* **318**: 71–76.
- Toth I, Neumann ID (2013). Animal models of social avoidance and social fear. *Cell Tissue Res* **354**: 107–118.
- Uekita T, Okanoya K (2011). Hippocampus lesions induced deficits in social and spatial recognition in *Octodon degus*. *Behav Brain Res* **219**: 302–309.
- Wöhr M, Silverman JL, Scattoni ML, Turner SM, Harris MJ, Saxena R *et al* (2012). Developmental delays and reduced pup ultrasonic vocalizations but normal sociability in mice lacking the postsynaptic cell adhesion protein neuroligin2. *Behav Brain Res* **251**: 50–64.
- Wood GE, Young LT, Reagan LP, McEwen BS (2003). Acute and chronic restraint stress alter the incidence of social conflict in male rats. *Horm Behav* **43**: 205–213.
- Wood GE, Norris EH, Waters E, Stoldt JT, McEwen BS (2008). Chronic immobilization stress alters aspects of emotionality and associative learning in the rat. *Behav Neurosci* **122**: 282–292.
- Yang M, Silverman JL, Crawley JN (2011). Automated three-chambered social approach task for mice. *Curr Protoc Neurosci* **8**: 8.26.
- Yizhar O, Fenno LE, Prigge M, Schneider F, Davidson TJ, O'Shea DJ *et al* (2011). Neocortical excitation/inhibition balance in information processing and social dysfunction. *Nature* **477**: 171–178.

Supplementary Information accompanies the paper on the Neuropsychopharmacology website (<http://www.nature.com/npp>)