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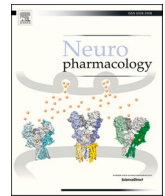
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Application of a pharmacological transcriptome filter identifies a shortlist of mouse glucocorticoid receptor target genes associated with memory consolidation

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ABSTRACT

Glucocorticoids regulate memory consolidation, facilitating long-term storage of relevant information to adequately respond to future stressors in similar conditions. This effect of glucocorticoids is well-established and is observed in multiple types of behaviour that depend on various brain regions. By and large, higher glucocorticoid levels strengthen event-related memory, while inhibition of glucocorticoid signalling impairs consolidation. The mechanism underlying this glucocorticoid effect remains unclear, but it likely involves the transcriptional effects of the glucocorticoid receptor (GR). We here used a powerful paradigm to investigate the transcriptional effects of GR in the dorsal hippocampus of mice after training in an auditory fear conditioning task, aiming to identify a shortlist of GR target genes associated to memory consolidation. Therefore, we utilized in an explorative study the properties of selective GR modulators (CORT108297 and CORT118335), alongside the endogenous agonist corticosterone and the classical GR antagonist RU486, to pinpoint GR-dependent transcriptional changes. First, we confirmed that glucocorticoids can modulate memory strength via GR activation. Subsequently, by assessing the specific effects of the available GR-ligands on memory strength, we established a pharmacological filter which we imposed on the hippocampal transcriptome data. This identified a manageable shortlist of eight genes by which glucocorticoids may modulate memory consolidation, warranting in-depth follow-up. Overall, we showcase the strength of the concept of pharmacological transcriptome filtering, which can be readily applied to other research topics with an established role of glucocorticoids.

1. Introduction

Stressors result in increased glucocorticoid secretion from the adrenal glands. Glucocorticoids in turn can bind to two receptor types which act as transcription factors: the glucocorticoid receptor (GR) and the mineralocorticoid receptor (MR) (de Kloet et al., 2005). Via these receptors glucocorticoids affect a multitude of processes throughout the body to cope with the stressor, such as redirecting energy supplies,

restoring homeostasis in the aftermath of the stress and memory formation (Sapolsky et al., 2000). By the latter, glucocorticoids enable long-term consolidation of relevant information so that an individual can adequately respond when exposed to similar conditions in the future (Roozendaal et al., 2009; Schwabe et al., 2012). This role of glucocorticoids on memory pertains to a multitude of different behaviours that each involve specific brain regions (de Quervain et al., 2017). While the modulation of memory consolidation by glucocorticoids is

Abbreviations: AFC, auditory fear conditioning; CORT, corticosterone; C108, CORT108297; C118, CORT118335; DEG, differentially expressed gene; GR, glucocorticoid receptor; MR, mineralocorticoid receptor; PCA, principal component analysis; RNAseq, RNA sequencing; SGRM, selective glucocorticoid receptor modulator.

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well-established, the underlying molecular mechanism has remained largely elusive, except for a clear involvement of GRs.

For instance, pharmacological inhibition of glucocorticoid signalling by the GR antagonist RU486 prevents long-term memory consolidation, whereas it has been reported that immediate conditioning was not impaired (Pugh et al., 1997; Zhou et al., 2010). This indicates that the slower transcriptional effects of GR are involved, which is in line with the memory-impairments observed in GR dimerization mutant mice that have impaired GR transcriptional activity (Oitzl et al., 2001). GR's transcriptional effects depend on the coregulators in the transcription complex, of which the recruitment in turn depends on the ligand bound to GR (Weikum et al., 2017). Therefore, the outcome of GR's transcriptional activity can be altered by selective glucocorticoid receptor modulators (SGRMs), which combine agonistic and antagonistic properties in a tissue- and cell-type specific manner (Viho et al., 2019). The compounds CORT108297 and CORT118335 were designed as selective GR antagonists, but both compounds were subsequently proven to act as SGRMs in both brain and liver based on their combined agonistic and antagonistic effects (Atucha et al., 2015; Koorneef et al., 2018; Nguyen et al., 2017; Solomon et al., 2014; Zalachoras et al., 2013). These SGRMs can be used as tools to further dissect the effects of glucocorticoids, both at the behavioural and the molecular level. For modulation of memory consolidation, CORT108297 was found to resemble corticosterone (without displaying any affinity for MR as corticosterone in rodents does) – promoting consolidation (Zalachoras et al., 2013), while CORT118335 impaired memory consolidation (Atucha et al., 2015). The characteristics of CORT118335 are of special interest as this compound can antagonise both GR and MR, while RU486 does not affect MR signalling but has well established progesterone receptor affinity (Healy et al., 1983; Hunt et al., 2012; Kroon et al., 2018). The combination of these compounds therefore enables distinction between GR's and MR's involvement in the behavioural outcome and allows further dissection at a transcriptional level.

We set out to utilise in an explorative study the properties of these SGRMs, alongside the endogenous agonist corticosterone and the classical GR antagonist RU486, to reduce the often obtained longlist of GR-target genes that is intrinsic to transcriptomic approaches, and thereby further dissect the role of glucocorticoids in memory consolidation. To this end, we used auditory fear conditioning (AFC), a behavioural paradigm susceptible to glucocorticoid modulation and involving – among several areas – the hippocampus (Antoine et al., 2014; Lesuis et al., 2021), to assess the effects these GR-ligands have on memory strength and on the hippocampal transcriptome. Based on the behavioural outcomes we established pharmacological filters which we imposed on the transcriptome data to identify a shortlist of GR-target genes implicated in the modulation of memory consolidation by glucocorticoids.

2. Material and methods

2.1. Animals

All animal studies were approved by the ethical committee of the University of Utrecht and the CCD (nr. AVD115002016644) and were in accordance with EU Directive 2010/63/EU for animal experiments. Adult (eight weeks old) male C57Bl6 mice were obtained from Envigo (the Netherlands) and left undisturbed for 1 week with *ad libitum* food and normal day/light cycle. Males were used based on the well-established effects of corticosterone on memory consolidation in literature (Atucha et al., 2015; Buurstedde et al., 2021; Lesuis et al., 2021; Meir Drexler and Wolf, 2017; Zalachoras et al., 2013). All animals were individually housed seven days before fear conditioning in the morning. One cohort of animals was used for behavioural analyses ($n = 10$ per group) and another cohort for molecular analyses ($n = 4-5$ per group). These group sizes are commonly used in explorative experimental animal studies; clearly, to reach better power follow-up studies in larger

groups would be necessary (Bonapersona et al., 2021). Animals were killed by decapitation 1.5 or 3 h after the training for molecular analysis. Animals in the basal control group were taken directly from their cage and killed without any training or treatment.

2.2. Auditory fear conditioning

Each mouse was individually placed into a chamber (30 cm × 24 cm × 26 cm) without stripes on the walls (context A). The floor consisted of a metal grid for foot shock application. During the first 3 min, mice were allowed to explore the chamber freely, then three tones (2.8 kHz, 78 dB) were played for 30 s and during the last 2 s of each tone a foot shock (0.2 mA) was applied (Lesuis et al., 2021). Thirty seconds after the last shock, mice were removed from the chamber, treatment was administered and the mice were placed back in their home cage. After each trial the box was cleaned with acetic acid (1%).

2.3. Retrieval

Twenty-four hours after training memory retrieval of animals in the behavioural cohort was tested in context B (a 30 cm × 24 cm × 26 cm chamber with vertical stripes on the walls, except for the room facing wall which was made of transparent Plexiglas). Testing trials lasted 11.5 min: In the first 3 min, mice were again allowed to freely explore the chamber. Then, the tone was played 6 times for 30 s with intervals of 1 min in between. After the last tone there was a 30 s interval after which the mice were returned to their home cages (Arp et al., 2016). After each trial the box was cleaned with ethanol (70%). The experiment was recorded and freezing behaviour was later manually scored through Observer Software (Noldus, the Netherlands).

2.4. Treatment

Immediately after the training session mice were injected subcutaneously with either 3 mg/kg corticosterone, 20 mg/kg CORT108297 (C108), 80 mg/kg CORT118335 (C118), 40 mg/kg RU486 or vehicle (100% DMSO) and placed back into their cage. The doses applied were based on the studies that previously characterized the effects of the CORT108297 and CORT118335 on behaviour (Atucha et al., 2015; Zalachoras et al., 2013), and investigated 3.0 mg/kg corticosterone in AFC (Hui et al., 2004). CORT108297 (20 mg/kg) was shown to reach the brain and result in occupancy of brain GRs comparable to 3 mg/kg corticosterone (Zalachoras et al., 2013). This was not shown in such a direct manner for CORT118335, yet multiple central effects have been described, including antagonism of exogenously administered corticosterone at present dose (Atucha et al., 2015; McGinn et al., 2021).

2.5. Corticosterone measurements

Corticosterone levels were measured in separate cohorts 1.5 and 3 h after AFC in trunk blood using a high sensitivity EIA kit (AC-15F1, Immunodiagnostic Systems: limit of detection is 0.17 ng/ml).

2.6. RNA sequencing

For RNA-sequencing (RNAseq) total RNA was isolated from dorsal hippocampal tissue 3 h after AFC, the timepoint at which glucocorticoids most extensively affect the hippocampal transcriptome even though plasma levels are already normalized (Morsink et al., 2006). Snap-frozen tissue was homogenized using a tissue homogenizer in lysis buffer of the NucleoSpin RNA kit (Macherey-Nagel). Total RNA was isolated according to the manufacturer's protocol and samples were sent for transcriptome sequencing at BGI Genomics. RNA quality of all samples was assessed using the RNA 6000 Nano kit on a Bioanalyzer (Agilent) and all samples passed the quality criteria for sequencing (RNA Integrity Number >7.0 and 28/18s ratio > 1.0). Stranded mRNA

libraries were constructed and 100 bp paired-end sequencing was performed on the DNBSseq platform resulting in >20 million reads per samples. RNAseq data have been deposited in NCBI's Gene Expression Omnibus and are accessible through GEO series accession number GSE202236.

2.7. RNAseq analysis

The Gentrapp pipeline, published as part of Bio Pipeline Execution Toolkit (Biopet, <https://biopet-docs.readthedocs.io>), was used for read quality control, alignment and quantification. Quality control was performed using FastQC and MultiQC. Reads were aligned to mm10 using GSnap aligner (version 2017-09-11). Gene-read quantification was performed using HTSeq-count (version 0.6.1) based on Ensembl release 88 of mm10. HTSeq-count output files were merged into a count matrix as input for differential gene expression analysis.

DESeq2 (version 1.29.4) was used for normalization of the data (median of ratio's method) and identification of differentially expressed genes (Love et al., 2014). For the differential expression analysis, we selected all genes which were expressed in a minimum of four replicates with >20 normalized counts, resulting in 15,193 genes in the analysis. One sample was identified as an outlier (sample 10 of the vehicle group) and removed from further analysis. Groups were analysed in pair-wise comparisons and a FDR adjusted p-value of 0.05 was used as a cut-off to determine differentially expressed genes unless stated differently (Sup. Table 1).

Gene ontology enrichment analysis was performed on all genes differentially expressed after AFC with the ViSEAGO package (version 1.4.0), using fisher's exact test with 0.01 as a significance cut-off (Brionne et al., 2019). Cytoscape (version 3.9.1) generated a connectivity-network based on reported protein-protein interaction (Shannon et al., 2003). Proteins encoded by all AFC-genes (adjusted p-value < 0.05) and of the genes most robustly differentially expressed after AFC (adjusted p-value < 0.01 and a log2 fold change of at least 0.5) were analysed. Densely connected sub-networks were subsequently detected using the MCODE algorithm (Bader and Hogue, 2003) and the associated biological processes were determined using Cytoscape's functional enrichment analysis.

2.8. GR-binding analysis

Publicly available chromatin immunoprecipitation data of GR was utilized to determine to which extent GR contributed to the differentially expressed genes after AFC. Data of three separate studies were downloaded, investigating GR DNA-binding in the rat hippocampus after corticosterone with or without adrenalectomy and after forced swim stress (Buurstedte et al., 2021; Mifsud et al., 2021; Polman et al., 2013). All genes associated to GR DNA-binding in at least one of the datasets were extracted and the percentage of AFC-genes associated to *in-vivo* GR DNA-binding was calculated.

2.9. qPCR validations

cDNA was synthesized from 1.000 ng of RNA using random hexamers and M-MLV reverse transcriptase (Promega) according to the manufacturer's protocol. Real-time quantitative PCR (RT-qPCR) was performed using GoTaq® qPCR Master Mix (Promega) with a CFX96 Touch™ Real-Time PCR Detection System (Bio-Rad). mRNA expression levels were normalized to housekeeping gene Rplp0 using the $2^{-\Delta\Delta CT}$ method with the AFC-vehicle group as calibrator. Used primer sequences were included as a supplementary table (Sup. Table 2).

2.10. Single-cell expression data

Single-cell mouse hippocampal expression data of the Allen Institute for Brain Science (Yao et al., 2021) was used to visualize the genes

identified by the pharmacological transcriptome filter by dotplot using Seurat's visualization tools with standard settings (version 3.1.5) as previously published (Viho et al., 2021). These public data indicate the gene expression levels under basal conditions as the mice were not exposed to any behavioural training or treatment.

2.11. Statistics

One-way ANOVAs were used for the analyses of plasma corticosterone levels Dunnett's multiple comparison tests were used as post-hoc. Freezing data were analysed by an ANOVA with treatment * tone as factors and predefined contrasts: corticosterone vs. Vehicle, CORT108297 vs. corticosterone, RU486 vs. Vehicle and CORT118335 vs. RU486. Analysis was subsequently repeated for all contrasts to expand the pharmacological transcriptome filter (6 treatment levels, and six consecutive tones). Gene expression data were analysed using one-way ANOVA following Sidak multiple comparison tests with predefined contrasts: CORT10927 vs. Veh, CORT118335 vs. CORT and RU486 vs. CORT. Statistical analyses of corticosterone levels and gene expression data were performed with GraphPad Prism 7 software (GraphPad Inc.) and freezing data were analysed in R (version 4.0.0).

3. Results

3.1. The experimental design for the pharmacological transcriptome filtering approach

Upon secretion endogenous glucocorticoids reach virtually all organs of which the vast majority expresses either GR, MR or both. The resulting transcriptional effects are extensive, often identifying a longlist of hundreds or thousands of (in)direct target genes, which hampers the identification of genes that are directly relevant for the studied biological process. We here introduce the concept of pharmacological transcriptome filtering using SGRMs to obtain a short- instead of a longlist and illustrate the feasibility of the approach in male mice after AFC (Fig. 1). The essence of this approach is to use several ligands for one receptor type that all have different molecular effects on gene expression. Only those genes that consistently correlate with the behavioural effects are then considered as potentially causal.

In the current study we used three separate cohorts. An untrained and untreated group of animals was used to determine baseline hippocampal gene expression (Cohort 1, Fig. 1A). A separate molecular cohort of animals was exposed to AFC and subsequent treatment with a specific set of GR-ligands to determine GR's molecular effects after 3 h (Cohort 2, Fig. 1B). Lastly, a behavioural cohort was ran in parallel to the molecular cohort to determine GR's role in AFC memory consolidation (Cohort 3, Fig. 1C). Based on the behavioural outcome of cohort 3 we selected suitable contrasts to impose on the transcriptome data obtained from cohort 2, enabling the identification of genes which expression pattern correspond to the functional outcome studied.

3.2. Glucocorticoid receptor activity regulates fear memory consolidation

Mice were subjected to AFC training. Corticosterone levels were significantly higher 1.5 h after AFC in the corticosterone and RU486 groups compared to vehicle group ($F(4,20) = 33.08$; p-value < 0.0001, Fig. 2A). Corticosterone levels after treatment with SGRMs CORT108297 and CORT118335 did not differ, indicating that HPA-axis feedback was not affected by these compounds. No differences in corticosterone levels were observed 3 h after AFC ($F(4,20) = 1.763$; p-value = 0.1760, Fig. 2B). Memory retrieval was determined 24 h after AFC by assessing freezing to six subsequent tones in another context. Initial freezing to the first tone and the level of freezing to subsequent tones differed per group (Fig. 2C). The average freezing percentage of all tones over time was used as a summary measure of memory strength, which was significantly affected by post-AFC treatment ($F(29,270) =$

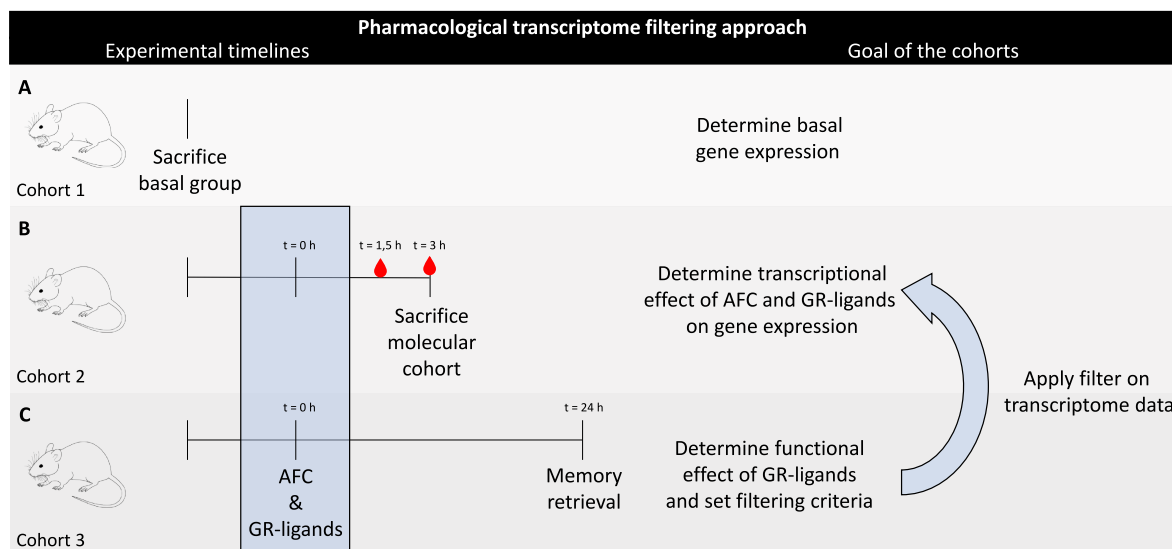


Fig. 1. Experimental design of pharmacological filtering approach.

Three separate cohorts were used to apply the pharmacological transcriptome filter based on Auditory Fear Conditioning (AFC) on the dorsal hippocampal transcriptome. A) Cohort 1: Untrained and untreated cohort to determine basal hippocampal gene expression. B) Cohort 2: AFC trained animals with post-training injection with GR-ligands to determine the subsequent transcriptional effects after 3 h. Corticosterone levels were determined at 1.5 and 3 h after AFC and treatment. C) Cohort 3: AFC trained animals with post-training injection with GR-ligands to determine behavioural effects by memory retrieval after 24 h.

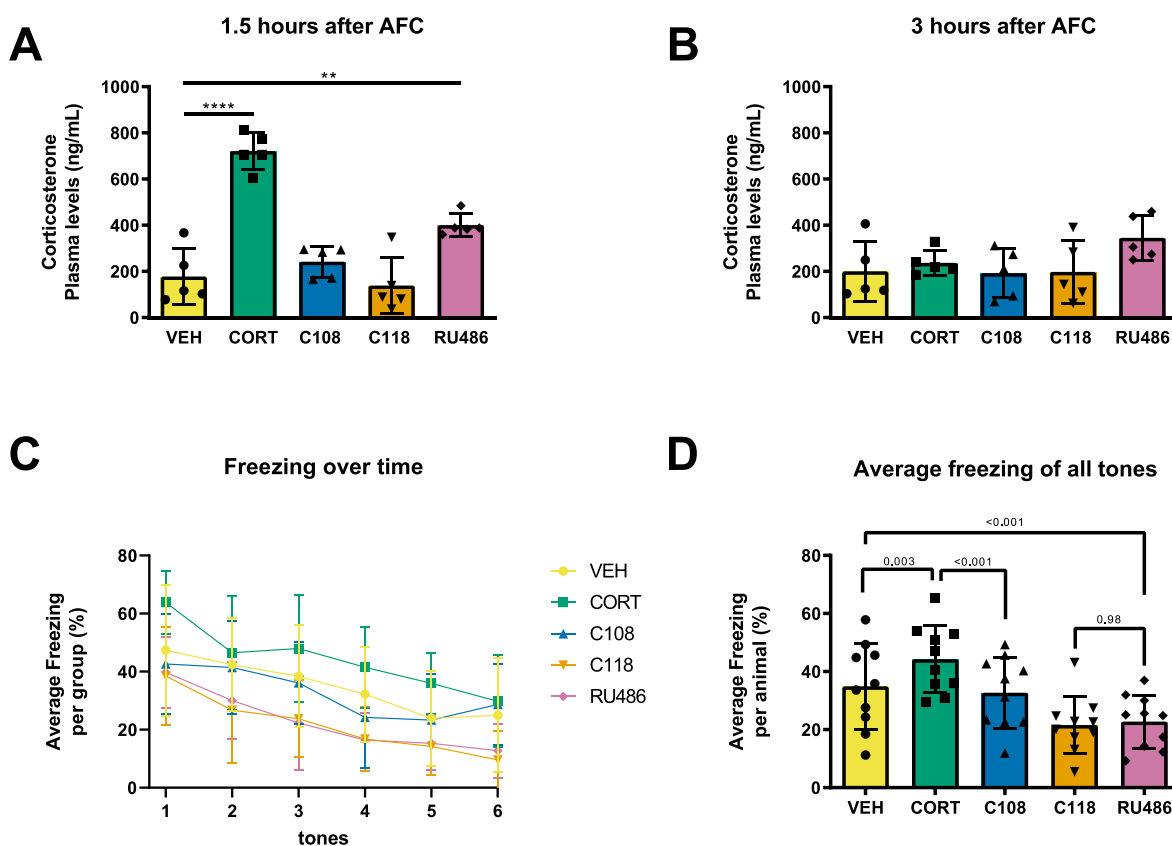


Fig. 2. Pharmacological modulation of GR activity affects memory consolidation.

Plasma corticosterone levels 1.5 h (A) and 3 h (B) after Auditory Fear Conditioning (AFC) (n = 5 per group). C) Average freezing over time per group and D) average freezing of all six tones per animals at memory retrieval testing 24 h after AFC (n = 10 per group). VEH: vehicle, CORT: corticosterone, C108: CORT108297, C118: CORT118335.

7.025; p-value < 0.0001, Fig. 2D). Corticosterone administration resulted in overall higher freezing, while treatment with the classic GR antagonist RU486 and the SGRM CORT118335 significantly reduced

overall freezing to similar extent. The latter points to impaired memory consolidation compared to the vehicle control group, where secretion of endogenous corticosterone forms an intrinsic part of the acquisition (and

consolidation) phase. Average freezing levels of mice treated with the SGRM CORT108297 were significantly lower compared to corticosterone treated animals yet comparable to the vehicle group, indicating that it did not affect the consolidation of this type of memory. Altogether, application of the pharmacological filter on the behavioural data confirmed GR as regulator of memory consolidation and identified contrasts to be applied in subsequent steps of the transcriptome analysis, with corticosterone as an agonist, CORT118335 and RU486 as antagonists and CORT108297 as an inactive compound in this paradigm.

3.3. Auditory fear conditioning strongly affects the hippocampal transcriptome

AFC affected the hippocampal transcriptome 3 h after training as evident from the separation between conditioned vehicle and basal control (untrained and untreated) animals in the principal component analysis (PCA, Fig. 3A). Differential gene expression analysis revealed the effect was extensive and identified 1,018 differentially expressed genes (DEGs) (455 up- and 563 down-regulated, Fig. 3B). Gene ontology analysis of these AFC-genes identified 110 enriched biological processes, 17 molecular functions and 16 cellular components (Sup. Table 3). Top terms included synapse-related processes (Fig. 3C) and transcription-related functions (Fig. 3D). Network analysis of all AFC-genes resulted in a large network with 27 densely connected subnetworks, of which the top three were related to kinase signalling, regulation of proliferation and glycosaminoglycans (Fig. 3E and Sup. Table 4). Analysis of the most robustly regulated genes (adjusted p-value < 0.01 and log₂ fold change > 0.5) identified ten densely connected subnetworks with only the top hit indicating a specific process: neurogenesis (Fig. 3F and Sup. Table 4). The contribution of endogenous glucocorticoids to the effect of AFC was evident as the top six DEGs included five established glucocorticoid responsive genes (*Dpf1*, *Fkbp5*, *Hif3a*, *Plin4* and *Tsc22d3*, Fig. 3G). Of all genes differentially expressed after AFC, 32.7% was associated to *in-vivo* GR DNA-binding based on three separate studies, once more confirming the role of hippocampal GR in AFC (Fig. 3H) (Buurstedte et al., 2021; Mifsud et al., 2021; Polman et al., 2013).

3.4. Differential modulation of the hippocampal transcriptome by GR-ligands

We hypothesized that the set of genes with altered expression would differ for each GR-ligand, with only limited overlap of genes that parallel behaviour. Therefore, we assessed how modulation of GR activity by each GR-ligand affected the hippocampal transcriptome 3 h after AFC training in comparison to AFC vehicle-injected animals, where elevation of corticosterone forms an intrinsic part of the test situation. Administration of exogenous corticosterone resulted in 84 DEGs (47 up- and 37 down-regulated, Fig. 4A). The SGRM CORT108297 most strongly affected the hippocampal transcriptome with 298 DEGs (154 up- and 144 down-regulated, Fig. 4B). Antagonist RU486 significantly affected the expression of 45 genes (5 up- and 40 down-regulated relative to AFC-vehicle, Fig. 4C) and the SGRM CORT118335 resulted in 46 DEGs (3 up- and 43 down-regulated, Fig. 4D). In previous characterizations of the SGRMs in relation to memory consolidation, CORT108297 predominantly acted as an agonist while CORT118335 acted more as a GR antagonist (Atucha et al., 2015; Zalachoras et al., 2013). Therefore, both SGRMs were also directly compared to corticosterone and RU486 respectively. Despite the difference in total DEGs between CORT108297 and corticosterone compared to vehicle, only 4 genes were significantly different between these compounds (Fig. 4E). Direct comparison of RU486 and CORT118335 did not reveal any DEGs (Fig. 4F), indicating the effects of these compounds on hippocampal genes expression were highly comparable. Overall, the effects of pharmacological modulation of GR activity after AFC were subtle, as was also evident from the lack of separation between the different GR-ligand-treated groups in the PCA plot (Fig. 4G).

3.5. Pharmacological transcriptome filter identifies putative GR-mediated memory associated genes

Our following step was to pinpoint which of the changes in the transcriptome ran in parallel with the regulatory effects GR exerted on memory consolidation. As corticosterone enhanced memory retrieval and both RU486 and CORT118335 impaired it, we first filtered on genes differentially expressed after additional corticosterone relative to vehicle and differentially expressed in the opposite direction by both RU486 and CORT118335. However, no transcripts met these criteria. Given the clear effects on memory retrieval, we decided to impose a bigger contrast on the transcriptome data by directly comparing the memory enhancing and impairing compounds. In order to again link this to our behavioural outcome we extended the analysis of our behavioural data to include the appropriate contrasts (Sup. Fig. 1). As RU486 and CORT118335 both impaired memory to similar extent, we filtered on genes differentially expressed between corticosterone in comparison to RU486 as well as CORT118335. Application of these criteria resulted in 15 genes (adjusted p-value < 0.1). To further reduce the shortlist of genes, we imposed an additional behaviour-based filter. While the freezing response after CORT108297 did not differ from vehicle-treatment, its effects on the transcriptome was substantial. Therefore, additional filtering was performed under the criterion that there was no differential expression between CORT108297 and vehicle. This further excluded two genes as potentially mediating the modulation of fear conditioning via GR (*Dbp* and *Ptgfrn*). Of this shortlist, eight were validated with a significant main effect by qPCR between the relevant groups and met the filtering criteria (Fig. 5A). For *Irak2* and *Nrros* we found a trend between CORT118335 and corticosterone based on the qPCR validation. These genes were kept on the shortlist as overall the data implicated their involvement. Of the other five genes, *Dzip11* and *Cdkn1a* did show a main effect, but also a trend level/significant difference between CORT108297 and vehicle. The main effect of post-AFC treatment could not be validated for *Lrig1*, *Tiam2* and *Bcl2l1* (Fig. 5B). The pharmacological transcriptome filter thus identified a shortlist of eight genes that closely follow the behavioural effects of corticosterone and the two functional antagonists. Five of these genes (*Fkbp5*, *Irak2*, *Lao1*, *Mthfd2* and *Pnpla2*) are likely directly regulated by GR, based on an association to proximal GR DNA-binding in the hippocampus (Fig. 3H).

Altogether, application of the pharmacological transcriptome filter resulted in eight genes for which a connection to GR-mediated fear memory was implicated based on the association of expression changes in the dorsal hippocampus in accordance with the behavioural effects.

3.6. Potential role of non-neuronal cells in GR-modulation of memory consolidation

The dorsal hippocampus is composed of various cell types and the assessed transcriptome provided an overview of all individual and potentially cell-specific effects combined. Publicly available single-cell data of the mouse hippocampal transcriptome under basal conditions (Yao et al., 2021) showed that expression of some genes on our shortlist was relatively comparable across cell types (*Lao1* and *Wbp1l*), while other genes showed a more exclusive pattern. This survey revealed that the majority of the genes identified by application of the pharmacological transcriptome filter were predominantly expressed in non-neuronal cells (*Cx3cr1*, *Irak2*, *Lao1*, *Nrros*, *Pnpla2* and *Wbp1l*), while *Fkbp5* prevailed in principal neurons and *Mthfd2* in GABAergic interneurons (Fig. 6). Expression of *Cx3cr1*, *Irak2* and *Nrros* was especially enriched in microglial cells, indicating a potential role of these and other non-neuronal cells in the modulation of memory consolidation by GR.

4. Discussion

Our goal was to better understand transcription of GR target genes

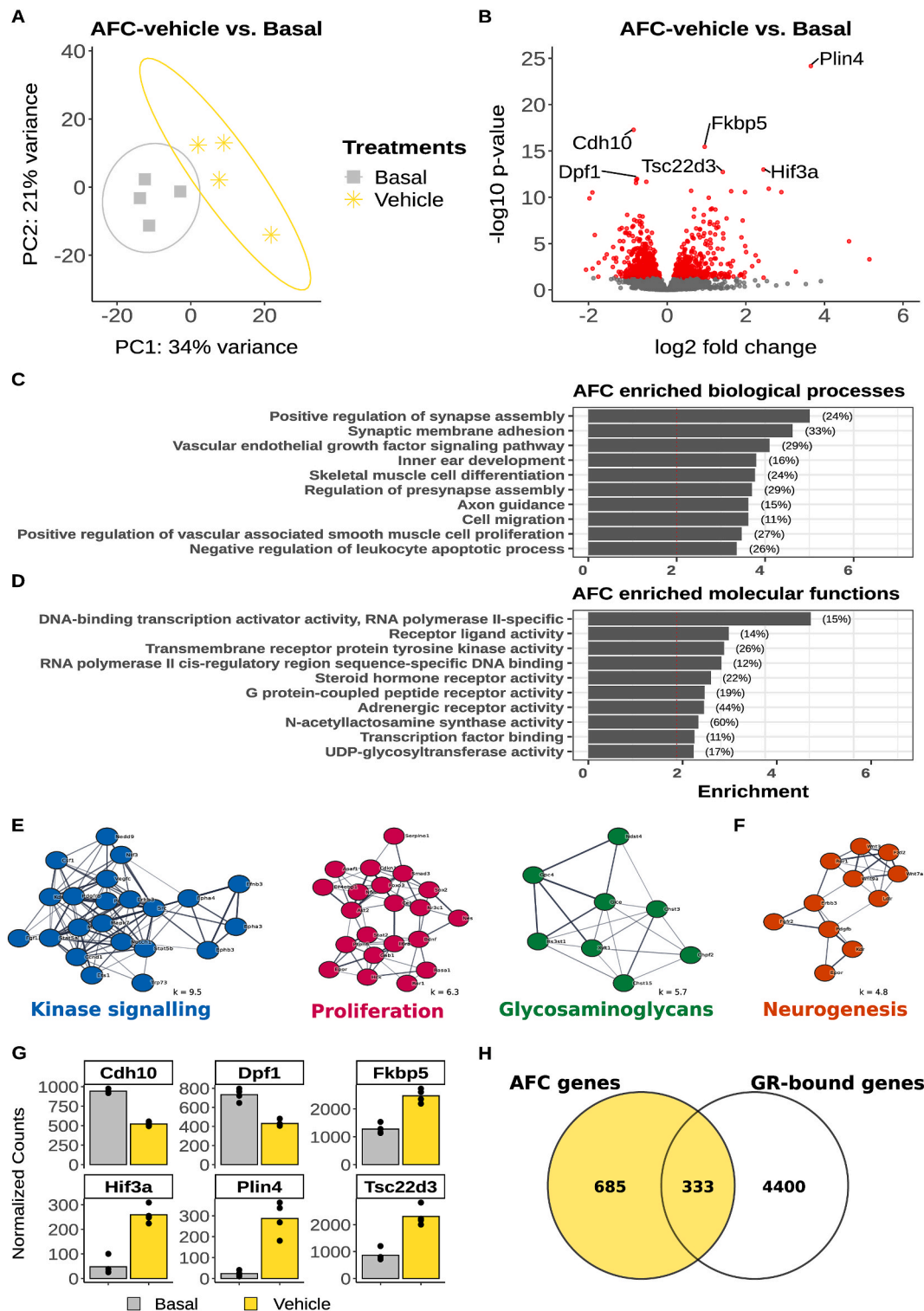


Fig. 3. Glucocorticoids drive the hippocampal transcriptome changes after auditory fear conditioning.

A) Principal component analysis plot visualising separation between vehicle-injected auditory fear conditioned (AFC) and basal control (untrained and untreated) animals based on the hippocampal transcriptome determined 3 h after training (n = 4 per group). B) Volcano plot visualising differentially expressed genes (DEGs) between vehicle-injected AFC and basal animals. Red dots represent DEGs (AFC-genes) at adjusted p-value 0.05, the six most significant genes are labelled. Top 10 of the GO term enrichment analyses on all AFC-genes for biological processes (C) and molecular functions (D). Top 3 dense networks revealed by the MCODE algorithm based on all AFC-genes (E) and AFC-genes with an adjusted p-value < 0.01 and log2 fold change > 0.5 (F). G) Normalized RNAseq count plots of the top six significantly DEGs (n = 4 per group). H) Venn-diagram visualising overlap between all AFC-genes and genes with associated proximal GR DNA-binding in the hippocampus based on three separate studies (Polman et al., Mifsud et al. and Buurstedte et al.).

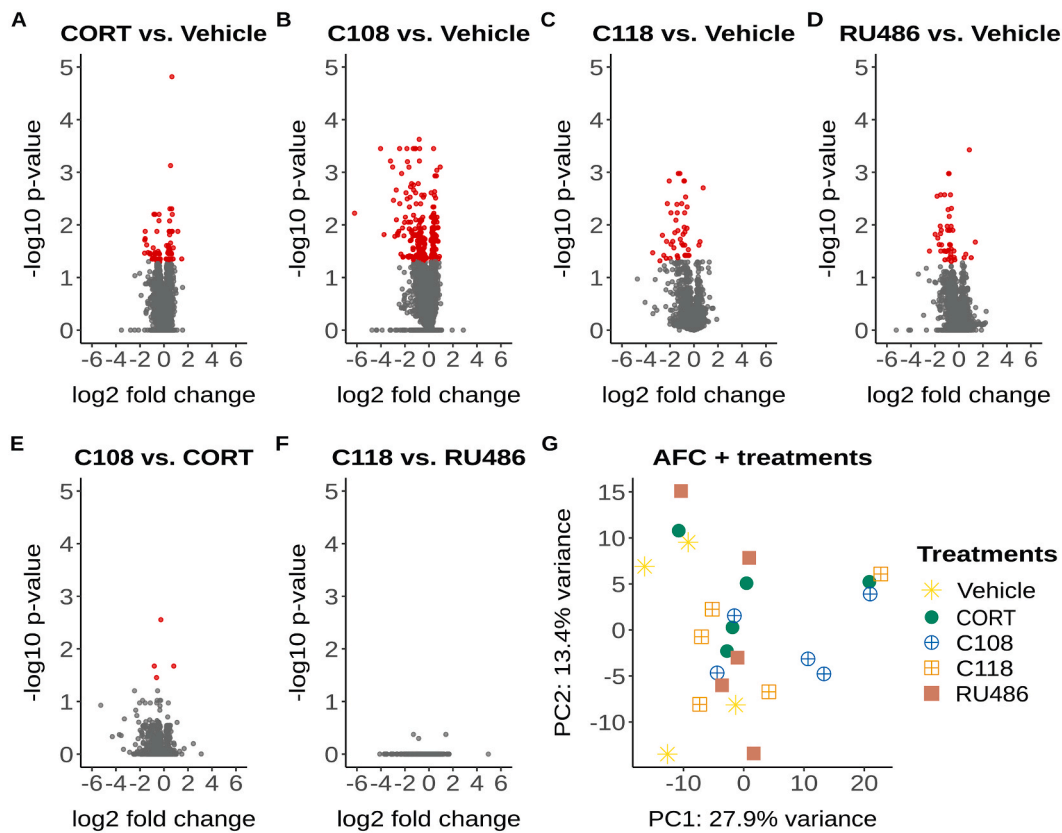


Fig. 4. Pharmacological modulation of GR activity subtly affects the hippocampal transcriptome after auditory fear conditioning.

Volcano plots visualising differentially expressed genes (DEGs) of corticosterone (A), CORT108297 (B), CORT118335 (C) and RU486 (D) compared to vehicle-injected auditory fear conditioned (AFC) animals and between CORT108297 vs. corticosterone (E) and CORT118335 vs. RU486 (F). G) Principal component analysis plot visualising the effect of treatment after AFC on the hippocampal transcriptome (n = 4-5 per group). CORT: corticosterone, C108: CORT108297, C118: CORT118335.

that may underly corticosterone effects on memory consolidation. We worked under the assumption that memory consolidation involves the hippocampus, and that the most direct way to explain effects of GR ligands is by their direct action on this brain region. To this end we established, using an explorative approach, functional contrasts based on how GR-ligands affected the memory strength after AFC and imposed these on hippocampal transcriptome data. By utilizing the selective properties of SGRMs CORT108297 and CORT118335 alongside the endogenous agonist corticosterone (vehicle group), exogenously applied corticosterone and the classical GR antagonist RU486, we identified eight genes by which glucocorticoids may modulate memory consolidation. We argue that such a ‘pharmacological transcriptome filtering’ is a viable strategy to shorten ‘longlists’ of candidate genes from omics approaches.

In many behavioural paradigms glucocorticoids increase memory strength, and inhibiting glucocorticoid signalling impairs memory strength (de Quervain et al., 2017; Finsterwald and Alberini, 2014). As AFC behaviour and hippocampal memory representation is susceptible to modulation by glucocorticoids (Lesuis et al., 2021), we selected this paradigm to test our pharmacological transcriptome filtering approach. Of note, AFC involves multiple brain regions and fear conditioning based on cues strongly depends on the amygdala, with a smaller role for the hippocampus. Yet, both areas were shown to be equally activated after fear conditioning training when measuring ERK1/2 (Antoine et al., 2014) and engrams show that fear conditioning activates hippocampal neurons as well (Denny et al., 2014; Liu et al., 2012; Rao-Ruiz et al., 2019). We therefore reasoned that the contrasts obtained by AFC memory retrieval are applicable to the hippocampal transcriptome data.

Using the hippocampus allows for more tissue and less heterogenous subnuclei than in case of the amygdala.

As expected, post-AFC exogenous administration of corticosterone significantly increased average freezing levels, while RU486 and CORT118335 decreased freezing compared to the vehicle control group, presumably due to inhibiting the effects of endogenous corticosterone secreted as part of the rather stressful learning circumstances (Atucha et al., 2015; Lesuis et al., 2021; Zalachoras et al., 2013). These results confirm that glucocorticoids can modulate memory strength via GR, this being the only receptor targeted by all three compounds. The unchanged corticosterone levels after SGRMs treatment make it very unlikely that effects of the compounds occurred via alterations in HPA-axis activity. Somewhat unexpectedly, treatment with CORT108297 did not affect AFC behaviour, while previously in rats CORT108297 affected memory in the passive avoidance task to a similar extent as corticosterone (Zalachoras et al., 2013). The difference may relate to either species or task, with different levels of endogenous glucocorticoids after AFC in comparison to the passive avoidance task. Altogether, the differential effects of pharmacological modulation of GR-activity on freezing behaviour enabled us to establish functional contrasts for subsequent filtering.

We assumed the mechanism of glucocorticoids was reflected at the mRNA level. A limitation of our data is that we did not address potential additional changes at the epigenetic level. The hippocampal transcriptome was strongly affected by AFC, with functional annotation indicating synaptic changes and a role for transcription and kinase signalling. These results are in accordance with literature that emphasizes the importance of transcription in memory consolidation (Alberini and

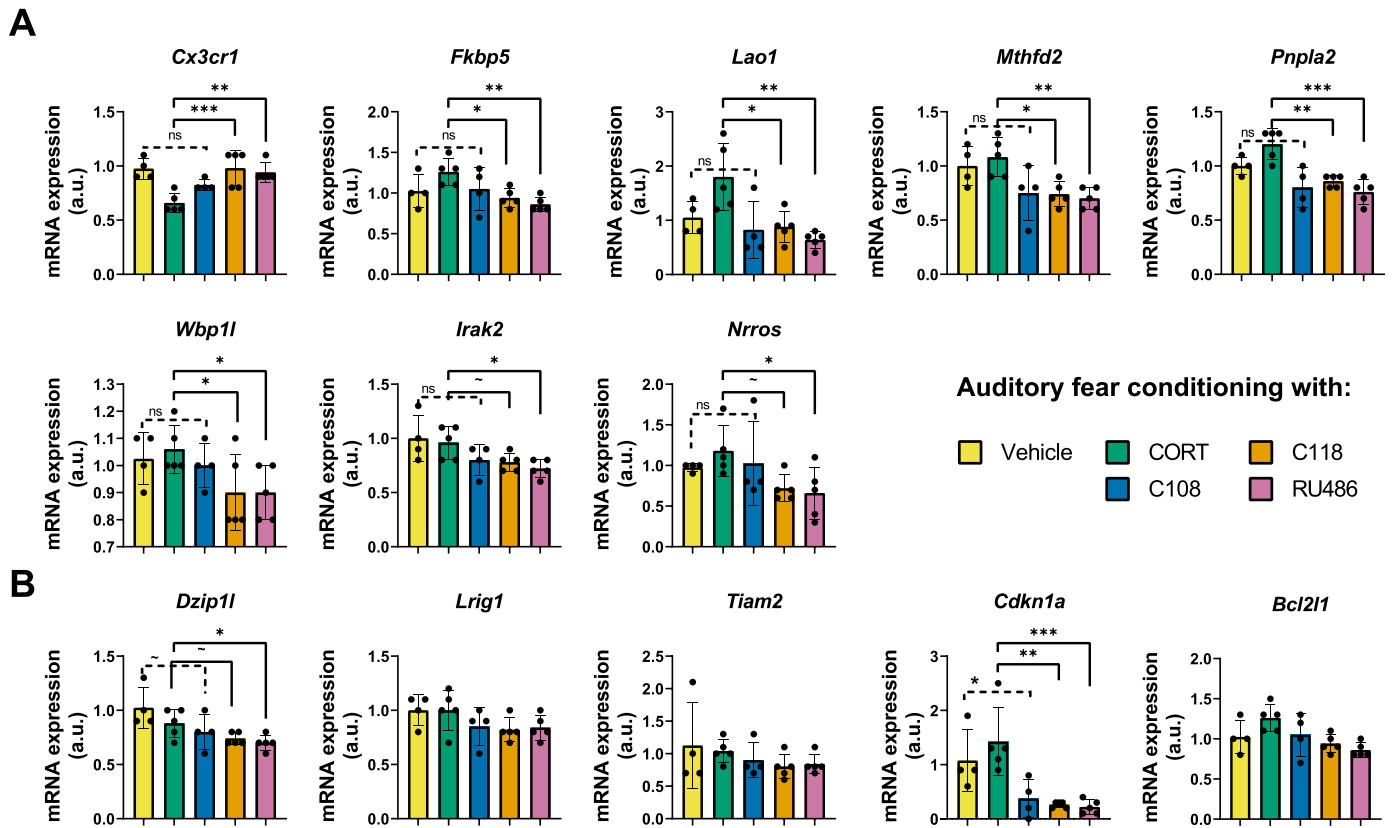


Fig. 5. Application of the pharmacological transcriptome filter identifies a shortlist of genes of which the expression parallels the behavioural outcome. qPCR analysis on vehicle, corticosterone, CORT108297, CORT118335 and RU486 groups for genes identified by applying the pharmacological transcriptome filter on the hippocampal transcriptome data (n = 4–5 per group). A) Shortlist genes validated by qPCR with a significant main effect of treatment and adhering to the pharmacological transcriptome filter. B) Genes not validated and therefore removed from the shortlist. * p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001. CORT: corticosterone, C108: CORT108297 and C118: CORT118335.

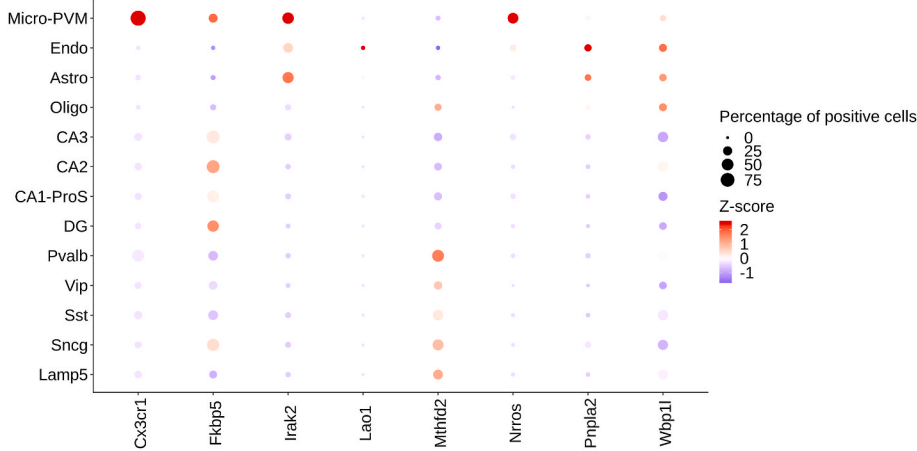


Fig. 6. Single-cell expression data implicate neuronal as well as non-neuronal cells in GR-modulation of memory consolidation. Dotplot visualising basal single-cell expression data in the hippocampus of untrained and untreated mice for the eight short-listed genes identified by application of the pharmacological transcriptome filter. Colour intensity of the dot represents expression level per cell type based on Z-scores (the centered log-normalized average expression) and dot size depicts the percentage of the corresponding cell type expressing the gene. Astro, astrocytes; CA1-ProS, *cornu ammonis* 1/pro-subiculum pyramidal cells; CA2, *cornu ammonis* 2 pyramidal cells; CA3, *cornu ammonis* 3 pyramidal cells; DG, dentate gyrus granule cells; Endo, endothelial cells; Lamp5, lysosomal associated membrane protein family 5 positive GABA neurons; Micro-PVM, microglial cells and perivascular macrophages; Oligo, oligodendrocytes; Pvalb, parvalbumin positive GABA neurons; Sncg, synuclein gamma positive GABA neurons; Sst, somatostatin positive GABA neurons; Vip, vasoactive intestinal peptide positive GABA neurons.

matostatin positive GABA neurons; Vip, vasoactive intestinal peptide positive GABA neurons.

Kandel, 2015). These changes likely include stress-induced corticosterone effects, given the presence of well-characterized GR targets in the set of regulated genes and extensive overlap with GR DNA-binding. The additional effects of pharmacological modulation of GR-activity (compared to the vehicle group) were limited – not only for exogenously administered corticosterone, but also for the classical GR antagonist RU486. Altogether, these relatively small effects in combination with the unexpected outcome of CORT108297 and the inherent

variation of behavioural experiments, prevented successful application of our predetermined filtering strategy including all treatments relative to vehicle. While the group size we applied is common for transcriptomic approaches, we like to emphasize the possibility of false negatives in our dataset. The current setup did however enable detection of significant changes with a log2 fold change as small as 0.16. As our initial filtering strategy needed adjustments, we defined a bigger contrast (corticosterone on the one hand versus CORT118335 and

RU486 on the other hand) based on the behavioural findings and on the transcriptome data, which still proved to be powerful.

The impact inclusion of SGRMs had on our pharmacological transcriptome filtering approach is evident, as addition of CORT118335 to the transcriptome filter (compared to merely filtering based on the corticosterone vs. RU486 contrast) reduced the shortlist by 26 genes (63%, from 41 to 15 DEGs at adjusted p -value < 0.1). After qPCR validation, our approach resulted in a manageable list of eight genes for more in-depth follow-up in future studies to establish and subsequently unravel their causal role in memory consolidation. It is important to note that these follow-up studies would need to also include female mice to determine possible sex-specific effects; as we only used male mice to assess the feasibility of our approach, this is a clear limitation in the interpretation of the current dataset. Further functional analysis of potential causal target genes is hampered by the fact that this would have to involve loss of GR responsiveness of these genes, rather than knockout or knockdown *per se*. This is not trivial, since in mice such an approach has been possible only on a single occasion, based on a fortuitous naturally occurring deletion in the mouse genome (So et al., 2009).

As GR is the only common target of corticosterone, CORT118335 and RU486, we confirmed the role of GR in increasing memory consolidation. Effects that are unique to CORT118335 may involve interference with MR. Early non-genomic effects mediated via MR may also have a role, but we did not address those here. Regulated genes in microglia should be regulated via GR, as these cells do not express MR (Viho et al., 2021). GR target genes in neuronal cells may also be an MR target, as has been established for e.g. FKBP5 (van Weert et al., 2019). We cannot exclude a role of MR in their regulation, but conclude that the pure GR antagonist RU486 suffices to attenuate their regulation after AFC.

Although the resulting shortlist contains the canonical GR-target gene *Fkbp5* (Paakinaho et al., 2010; Scharf et al., 2011), it did not become a simple reiteration of established GR-target genes (Juszczak and Stankiewicz, 2018). Based on the assessed GR DNA-binding data, the seven other genes likely respond to GR in a more context-dependent manner. The role of *Cx3cr1* and *Lao1* in behaviour and memory was previously studied using knockout mouse models. *Cx3cr1* encodes for a fractalkine receptor via which microglial cells can bi-directionally communicate with neurons, a signalling pathway associated with various neurological disorders (Pawelec et al., 2020; Wolf et al., 2013). Behavioural assessment of *Cx3cr1* KO mice revealed an anxiolytic-like phenotype and improved contextual memory (Bolos et al., 2018; Liu et al., 2020). These effects fit with the lower expression levels we observed after corticosterone administration compared to CORT118335 and RU486. Knockout of *Lao1*, an oxidase involved in amino acid metabolism, resulted in impaired fear learning and memory, reportedly due to low acetylcholine levels (Usuda et al., 2018); the present observations are in line with this earlier study. Direct involvement in behaviour or memory of any kind has to date not been studied for the remaining five genes (*Mthfd2*, *Pnpla2*, *Wbp1l*, *Nrros* and *Irak2*). Earlier, *Mthfd2* and *Nrros* affected the levels of reactive oxygen species (Wong et al., 2017; Yu et al., 2015), of which excessive increases are associated with decreased performance in cognition-based behavioural paradigms (Kishida and Klann, 2007; Massaad and Klann, 2011). The established (in)direct functions of a subset of the genes in our shortlist confirms the notion that this approach enables identification of relevant targets and guides future studies into a causal relationship.

Of note, many genes are - at a basal level - predominantly expressed in non-neuronal cells, an observation in line with growing evidence for the role of glial cells in stress and behaviour (Sanguino-Gomez et al., 2021; Wang et al., 2020). However, we cannot rule out that increases in gene expression occurred in cells that basally did not express said gene, indicating the need for validation. In addition, glucocorticoids were found to consistently regulate expression of non-neuronal genes and GR was shown to be important in astrocytes and microglia (Juszczak and Stankiewicz, 2018; Picard et al., 2021; Tertilt et al., 2018). Together, this also advocates for further experiments with cell-type specific knockouts

of GR to examine if the modulatory effect of glucocorticoids on memory consolidation is perhaps exerted by a specific cell type. As three genes on our shortlist are predominantly expressed in microglia, we propose these cells as an interesting starting point.

To conclude, the concept of pharmacological transcriptome filtering applied in this study is based on the properties of the SGRMs, including different receptor specificity and a combination of agonistic and antagonistic effects. Binding of the SGRMs to the GR leads to a unique interactome of coregulators, which in turn results in tissue- and cell-type specific transcriptional effects (Viho et al., 2019; Weikum et al., 2017). The postulated concept relies on the assumption that treatments that have a similar functional outcome, will also similarly affect the underlying molecular mechanism. Therefore, the common denominators (in this study differentially expressed genes) are likely to be somehow involved in the functional outcome studied. While in the current study we focussed on the role of glucocorticoids in memory consolidation, the concept of pharmacological transcriptome filtering can be applied to many directions of research with an established role of glucocorticoids or other transcriptional regulators.

Declaration of competing interest

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CRediT authorship contribution statement

Jacobus C. Buurstedte: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, and, Visualization. **Eduardo H.L. Umeoka:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, and, Writing – review & editing. **Marcia Santos da Silva:** Conceptualization, Methodology, Validation, Investigation, and, Writing – review & editing. **Harm J. Krugers:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, and, Supervision. **Marian Joëls:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision, and, Funding acquisition. **Onno C. Meijer:** Conceptualization, Methodology, Validation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, and, Funding acquisition.

Declaration of competing interest

Authors have no competing interests to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.neuropharm.2022.109186>.

References

- Alberini, C.M., Kandel, E.R., 2015. The regulation of transcription in memory consolidation. *Cold Spring Harbor Perspect. Biol.* 7.
- Antoine, B., Serge, L., Jocelyne, C., 2014. Comparative dynamics of MAPK/ERK signalling components and immediate early genes in the hippocampus and amygdala following contextual fear conditioning and retrieval. *Brain Struct. Funct.* 219, 415–430.
- Arp, J.M., ter Horst, J.P., Loi, M., den Blaauwen, J., Bangert, E., Fernandez, G., Joels, M., Oitzl, M.S., Krugers, H.J., 2016. Blocking glucocorticoid receptors at adolescent age prevents enhanced freezing between repeated cue-exposures after conditioned fear in adult mice raised under chronic early life stress. *Neurobiol. Learn. Mem.* 133, 30–38.
- Atucha, E., Zalachoras, I., van den Heuvel, J.K., van Weert, L.T.C.M., Melchers, D., Mol, I.M., Belanoff, J.K., Houtman, R., Hunt, H., Roozendaal, B., Meijer, O.C., 2015. A mixed glucocorticoid/mineralocorticoid selective modulator with dominant antagonism in the male rat brain. *Endocrinology* 156, 4105–4114.
- Bader, G.D., Hogue, C.W., 2003. An automated method for finding molecular complexes in large protein interaction networks. *BMC Bioinf.* 4.
- Bolos, M., Perea, J.R., Terreros-Roncal, J., Pallas-Bazarra, N., Jurado-Arjona, J., Avila, J., Llorens-Martin, M., 2018. Absence of microglial CX3CR1 impairs the synaptic integration of adult-born hippocampal granule neurons. *Brain Behav. Immun.* 68, 76–89.
- Bonapersona, V., Hoijsink, H., Consortium, R., Sarabdjitsingh, R.A., Joels, M., 2021. Increasing the statistical power of animal experiments with historical control data. *Nat. Neurosci.* 24, 470–477.
- Bronne, A., Juanchich, A., Hennequet-Antier, C., 2019. ViSEAGO: a Bioconductor package for clustering biological functions using Gene Ontology and semantic similarity. *BioData Min.* 12.
- Buurstedde, J.C., van Weert, L.T.C.M., Colucci, P., Gentenaar, M., Viho, E.M.G., Koorneef, L.L., Schoonderwoerd, R.A., Lanooij, S.D., Moustakas, I., Balog, J., Mei, H.L., Kielbasa, S.M., Campolongo, P., Roozendaal, B., Meijer, O.C., 2021. Hippocampal glucocorticoid target genes associated with enhancement of memory consolidation. *Eur. J. Neurosci.*
- de Kloet, E.R., Joels, M., Holsboer, F., 2005. Stress and the brain: from adaptation to disease. *Nat. Rev. Neurosci.* 6, 463–475.
- de Quervain, D., Schwabe, L., Roozendaal, B., 2017. Stress, glucocorticoids and memory: implications for treating fear-related disorders. *Nat. Rev. Neurosci.* 18, 7–19.
- Denny, C.A., Kheirbek, M.A., Alba, E.L., Tanaka, K.F., Brachman, R.A., Laughman, K.B., Tomm, N.K., Turi, G.F., Losonczy, A., Hen, R., 2014. Hippocampal memory traces are differentially modulated by experience, time, and adult neurogenesis. *Neuron* 83, 189–201.
- Finsterswald, C., Alberini, C.M., 2014. Stress and glucocorticoid receptor-dependent mechanisms in long-term memory: from adaptive responses to psychopathologies. *Neurobiol. Learn. Mem.* 112, 17–29.
- Healy, D.L., Chrousos, G.P., Schulte, H.M., Williams, R.F., Gold, P.W., Baulieu, E.E., Hodgen, G.D., 1983. Pituitary and adrenal responses to the anti-progestin and anti-glucocorticoid steroid RU 486 in primates. *J. Clin. Endocrinol. Metab.* 57, 863–865.
- Hui, G.K., Figueroa, I.R., Poytress, B.S., Roozendaal, B., McGaugh, J.L., Weinberger, N.M., 2004. Memory enhancement of classical fear conditioning by post-training injections of corticosterone in rats. *Neurobiol. Learn. Mem.* 81, 67–74.
- Hunt, H.J., Ray, N.C., Hynd, G., Sutton, J., Sajad, M., O'Connor, E., Ahmed, S., Lockett, P., Daly, S., Buckley, G., Clark, R.D., Roe, R., Blasey, C., Belanoff, J., 2012. Discovery of a novel non-steroidal GR antagonist with in vivo efficacy in the olanzapine-induced weight gain model in the rat. *Bioorg. Med. Chem. Lett* 22, 7376–7380.
- Juszczak, G.R., Stankiewicz, A.M., 2018. Glucocorticoids, genes and brain function. *Prog. Neuro-Psychopharmacol. Biol. Psychiatry* 82, 136–168.
- Kishida, K.T., Klann, E., 2007. Sources and targets of reactive oxygen species in synaptic plasticity and memory. *Antioxidants Redox Signal.* 9, 233–244.
- Koorneef, L.L., van den Heuvel, J.K., Kroon, J., Boon, M.R., 't Hoen, P.A.C., Hettne, K.M., van de Velde, N.M., Kolenbrander, K.B., Streefland, T.C.M., Mol, I.M., Sips, H.C.M., Kielbasa, S.M., Mei, H.L., Belanoff, J.K., Pereira, A.M., Oosterveer, M.H., Hunt, H., Rensen, P.C.N., Meijer, O.C., 2018. Selective glucocorticoid receptor modulation prevents and reverses nonalcoholic fatty liver disease in male mice. *Endocrinology* 159, 3925–3936.
- Kroon, J., Koorneef, L.L., van den Heuvel, J.K., Verzijl, C.R.C., van de Velde, N.M., Mol, I.M., Sips, H.C.M., Hunt, H., Rensen, P.C.N., Meijer, O.C., 2018. Selective glucocorticoid receptor antagonist CORT125281 activates Brown adipose tissue and alters lipid distribution in male mice. *Endocrinology* 159, 535–546.
- Lesuis, S.L., Brosens, N., Immerzeel, N., van der Loo, R.J., Mitri, M., Bielefeld, P., Fitzsimons, C.P., Lucassen, P.J., Kushner, S.A., van den Oever, M.C., Krugers, H.J., 2021. Glucocorticoids promote fear generalization by increasing the size of a dentate gyrus engram cell population. *Biol. Psychiatry* 90, 494–504.
- Liu, X., Ramirez, S., Pang, P.T., Puryear, C.B., Govindarajan, A., Deisseroth, K., Tonegawa, S., 2012. Optogenetic stimulation of a hippocampal engram activates fear memory recall. *Nature* 484, 381–U415.
- Liu, Y., Zhang, T.X., Meng, D.W., Sun, L., Yang, G.L., He, Y.T., Zhang, C., 2020. Involvement of CX3CL1/CX3CR1 in depression and cognitive impairment induced by chronic unpredictable stress and relevant underlying mechanism. *Behav. Brain Res.* 381.
- Love, M.I., Huber, W., Anders, S., 2014. Moderated estimation of fold change and dispersion for RNA-seq data with DESeq2. *Genome Biol.* 15.
- Massaad, C.A., Klann, E., 2011. Reactive oxygen species in the regulation of synaptic plasticity and memory. *Antioxidants Redox Signal.* 14, 2013–2054.
- McGinn, M.A., Tunstall, B.J., Schlosburg, J.E., Gregory-Flores, A., George, O., de Guglielmo, G., Mason, B.J., Hunt, H.J., Karst, H., Joels, M., Kloet, E.R., Datson, N.A., 2021. Glucocorticoid receptor modulators decrease alcohol self-administration in male rats. *Neuropharmacology* 188.
- Meir Drexler, S., Wolf, O.T., 2017. The role of glucocorticoids in emotional memory reconsolidation. *Neurobiol. Learn. Mem.* 142, 126–134.
- Mifsud, K.R., Kennedy, C.L.M., Salatino, S., Sharma, E., Price, E.M., Haque, S.N., Gialeli, A., Goss, H.M., Panchenko, P.E., Broxholme, J., Engledow, S., Lockstone, H., Llana, O.C., Reul, J.M.H.M., 2021. Distinct regulation of hippocampal neuroplasticity and ciliary genes by corticosteroid receptors. *Nat. Commun.* 12.
- Morsink, M.C., Steenbergen, P.J., Vos, J.B., Karst, H., Joels, M., Kloet, E.R., Datson, N.A., 2006. Acute activation of hippocampal glucocorticoid receptors results in different waves of gene expression throughout time. *J. Neuroendocrinol.* 18, 239–252.
- Nguyen, E.T., Streicher, J., Berman, S., Caldwell, J.L., Ghisays, V., Estrada, C.M., Wulsin, A.C., Solomon, M.B., 2017. A mixed glucocorticoid/mineralocorticoid receptor modulator dampens endocrine and hippocampal stress responsivity in male rats. *Physiol. Behav.* 178, 82–92.
- Oitzl, M.S., Reichardt, H.M., Joels, M., de Kloet, E.R., 2001. Point mutation in the mouse glucocorticoid receptor preventing DNA binding impairs spatial memory. In: *Proceedings of the National Academy of Sciences of the United States of America*, 98, pp. 12790–12795.
- Paakinaho, V., Makkonen, H., Jaaskelainen, T., Palvimäki, J.J., 2010. Glucocorticoid receptor activates poised FKBP51 locus through long-distance interactions. *Mol. Endocrinol.* 24, 511–525.
- Pawelec, P., Ziemka-Nalecz, M., Sypecka, J., Zalewska, T., 2020. The impact of the CX3CL1/CX3CR1 Axis in neurological disorders. *Cells* 9.
- Picard, R., Bisht, K., Poggini, S., Garofalo, S., Golia, M.T., Basilico, B., Abdallah, F., Albanese, N.C., Amrein, I., Vernoux, N., Sharma, K., Hui, C.W., Savage, J.C., Limatola, C., Ragozzino, D., Maggi, L., Branchi, I., Tremblay, L., 2021. Microglial-glucocorticoid receptor depletion alters the response of hippocampal microglia and neurons in a chronic unpredictable mild stress paradigm in female mice. *Brain Behav. Immun.* 97, 423–439.
- Polman, J.A.E., de Kloet, E.R., Datson, N.A., 2013. Two populations of glucocorticoid receptor-binding Sites in the male rat hippocampal genome. *Endocrinology* 154, 1832–1844.
- Pugh, C.R., Tremblay, D., Fleshner, M., Rudy, J.W., 1997. A selective role for corticosterone in contextual-fear conditioning. *Behav. Neurosci.* 111, 503–511.
- Rao-Ruiz, P., Couey, J.J., Marcelo, I.M., Bouwkamp, C.G., Slump, D.E., Matos, M.R., van der Loo, R.J., Martins, G.J., van den Hout, M., van IJcken, W.F., Costa, R.M., van den Oever, M.C., Kushner, S.A., 2019. Engram-specific transcriptome profiling of contextual memory consolidation. *Nat. Commun.* 10.
- Roozendaal, B., McEwen, B.S., Chattarji, S., 2009. Stress, memory and the amygdala. *Nat. Rev. Neurosci.* 10, 423–433.
- Sanguino-Gomez, J., Buurstedde, J.C., Abiega, O., Fitzsimons, C.P., Lucassen, P.J., Eggen, B.J.L., Lesuis, S.L., Meijer, O.C., Krugers, H.J., 2021. An emerging role for microglia in stress-effects on memory. *Eur. J. Neurosci.*
- Sapolsky, R.M., Romero, L.M., Munck, A.U., 2000. How do glucocorticoids influence stress responses? Integrating permissive, suppressive, stimulatory, and preparative actions. *Endocr. Rev.* 21, 55–89.
- Scharf, S.H., Liebl, C., Binder, E.B., Schmidt, M.V., Müller, M.B., 2011. Expression and regulation of the Fkbp5 gene in the adult mouse brain. *PLoS One* 6.
- Schwabe, L., Joels, M., Roozendaal, B., Wolf, O.T., Oitzl, M.S., 2012. Stress effects on memory: an update and integration. *Neurosci. Biobehav. Rev.* 36, 1740–1749.
- Shannon, P., Markiel, A., Ozier, O., Baliga, N.S., Wang, J.T., Ramage, D., Amin, N., Schwikowski, B., Ideker, T., 2003. Cytoscape: a software environment for integrated models of biomolecular interaction networks. *Genome Res.* 13, 2498–2504.
- So, A.Y.L., Bernal, T.U., Pillsbury, M.L., Yamamoto, K.R., Feldman, B.J., 2009. Glucocorticoid regulation of the circadian clock modulates glucose homeostasis. In: *Proceedings of the National Academy of Sciences of the United States of America*, 106, pp. 17582–17587.
- Solomon, M.B., Wulsin, A.C., Rice, T., Wick, D., Myers, B., McKlveen, J., Flak, J.N., Ulrich-Lai, Y., Herman, J.P., 2014. The selective glucocorticoid receptor antagonist CORT 108297 decreases neuroendocrine stress responses and immobility in the forced swim test. *Horm. Behav.* 65, 363–371.
- Tertil, M., Skupio, U., Barut, J., Dubovyk, V., Wawrzczak-Bargiela, A., Soltys, Z., Golda, S., Kudla, L., Wiktorowska, L., Szklarczyk, K., Korostynski, M., Przewlocki, R., Slezak, M., 2018. Glucocorticoid receptor signaling in astrocytes is required for aversive memory formation. *Transl. Psychiatry* 8.
- Usuda, K., Kawase, T., Shigeno, Y., Fukuzawa, S., Fujii, K., Zhang, H.L., Tsukahara, T., Tomonaga, S., Watanabe, G., Jin, W.Z., Nagaoka, K., 2018. Hippocampal metabolism of amino acids by L-amino acid oxidase is involved in fear learning and memory. *Sci. Rep.* 8.
- van Weert, L., Buurstedde, J.C., Sips, H.C.M., Vettorazzi, S., Mol, I.M., Hartmann, J., Prekovic, S., Zwart, W., Schmidt, M.V., Roozendaal, B., Tuckermann, J.P., Sarabdjitsingh, R.A., Meijer, O.C., 2019. Identification of mineralocorticoid receptor target genes in the mouse hippocampus. *J. Neuroendocrinol.* 31, e12735.

- Viho, E.M.G., Buurstedde, J.C., Berkhout, J.B., Mahfouz, A., Meijer, O.C., 2021. Cell type specificity of glucocorticoid signaling in the adult mouse hippocampus. *J. Neuroendocrinol.*
- Viho, E.M.G., Buurstedde, J.C., Mahfouz, A., Koorneef, L.L., van Weert, L.T.C.M., Houtman, R., Hunt, H.J., Kroon, J., Meijer, O.C., 2019. Corticosteroid action in the brain: the potential of selective receptor modulation. *Neuroendocrinology* 109, 266–276.
- Wang, C., Yue, H.M., Hu, Z.C., Shen, Y.W., Ma, J., Li, J., Wang, X.D., Wang, L., Sun, B.G., Shi, P., Wang, L., Gu, Y., 2020. Microglia mediate forgetting via complement-dependent synaptic elimination. *Science* 367, 688.
- Weikum, E.R., Knuesel, M.T., Ortlund, E.A., Yamamoto, K.R., 2017. Glucocorticoid receptor control of transcription: precision and plasticity via allostery. *Nat. Rev. Mol. Cell Biol.* 18, 159–174.
- Wolf, Y., Yona, S., Kim, K.W., Jung, S., 2013. Microglia, seen from the CX3CR1 angle. *Front. Cell. Neurosci.* 7, 26.
- Wong, K., Noubade, R., Manzanillo, P., Ota, N., Foreman, O., Hackney, J.A., Friedman, B. A., Pappu, R., Searce-Levie, K., Ouyang, W.J., 2017. Mice deficient in NRROS show abnormal microglial development and neurological disorders. *Nat. Immunol.* 18, 633.
- Yao, Z., van Velthoven, C.T.J., Nguyen, T.N., Goldy, J., Sedeno-Cortes, A.E., Baftizadeh, F., Bertagnoli, D., Casper, T., Chiang, M., Crichton, K., Ding, S.L., Fong, O., Garren, E., Glandon, A., Gouwens, N.W., Gray, J., Graybuck, L.T., Hawrylycz, M.J., Hirschstein, D., Kroll, M., Lathia, K., Lee, C., Levi, B., McMillen, D., Mok, S., Pham, T., Ren, Q., Rimorin, C., Shapovalova, N., Sulc, J., Sunkin, S.M., Tieu, M., Torkelson, A., Tung, H., Ward, K., Dee, N., Smith, K.A., Tasic, B., Zeng, H., 2021. A taxonomy of transcriptomic cell types across the isocortex and hippocampal formation. *Cell* 184, 3222–3241 e3226.
- Yu, S., Jang, Y., Paik, D., Lee, E., Park, J.J., 2015. Nmdmc overexpression extends *Drosophila* lifespan and reduces levels of mitochondrial reactive oxygen species. *Biochem. Biophys. Res. Commun.* 465, 845–850.
- Zalachoras, I., Houtman, R., Atucha, E., Devos, R., Tijssen, A.M.I., Hu, P., Lockey, P.M., Datson, N.A., Belanoff, J.K., Lucassen, P.J., Joels, M., de Kloet, E.R., Roozendaal, B., Hunt, H., Meijer, O.C., 2013. Differential targeting of brain stress circuits with a selective glucocorticoid receptor modulator. In: *Proceedings of the National Academy of Sciences of the United States of America*, 110, pp. 7910–7915.
- Zhou, M., Bakker, E.H.M., Velzing, E.H., Berger, S., Oitzl, M., Joels, M., Krugers, H.J., 2010. Both mineralocorticoid and glucocorticoid receptors regulate emotional memory in mice. *Neurobiol. Learn. Mem.* 94, 530–537.