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RESEARCH ARTICLE

Unpredictable chronic stress decreases inhibitory avoidance learning in Tuebingen long-fin zebrafish: stronger effects in the resting phase than in the active phase

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ABSTRACT

Zebrafish (*Danio rerio* Hamilton) are increasingly used as a model to study the effects of chronic stress on brain and behaviour. In rodents, unpredictable chronic stress (UCS) has a stronger effect on physiology and behaviour during the active phase than during the resting phase. Here, we applied UCS during the daytime (active phase) for 7 and 14 days or during the night-time (resting phase) for 7 nights in an in-house-reared Tuebingen long-fin (TLF) zebrafish strain. Following UCS, inhibitory avoidance learning was assessed using a 3 day protocol where fish learn to avoid swimming from a white to a black compartment where they will receive a 3 V shock. Latencies of entering the black compartment were recorded before training (day 1; first shock) and after training on day 2 (second shock) and day 3 (no shock, tissue sampling). Fish whole-body cortisol content and expression levels of genes related to stress, fear and anxiety in the telencephalon were quantified. Following 14 days of UCS during the day, inhibitory avoidance learning decreased (lower latencies on days 2 and 3); minor effects were found following 7 days of UCS. Following 7 nights of UCS, inhibitory avoidance learning decreased (lower latency on day 3). Whole-body cortisol levels showed a steady increase compared with controls (100%) from 7 days of UCS (139%), to 14 days of UCS (174%) to 7 nights of UCS (231%), suggestive of an increasing stress load. Only in the 7 nights of UCS group did expression levels of corticoid receptor genes (*mr*, *grα*, *grβ*) and of *bdnf* increase. These changes are discussed as adaptive mechanisms to maintain neuronal integrity and prevent overload, and as being indicative of a state of high stress load. Overall, our data suggest that stressors during the resting phase have a stronger impact than during the active phase. Our data warrant further studies on the effect of UCS on stress axis-related genes, especially *grβ*; in mammals this receptor has been implicated in glucocorticoid resistance and depression.

KEY WORDS: *Danio rerio*, Behaviour, Telencephalon, Gene expression, Diurnal effects

INTRODUCTION

An upcoming research area is the use of zebrafish as a model to study the effects of chronic stress on brain and behaviour in relation to depression, anxiety and other mood-related disorders (Chakravarty et al., 2013; Gerlai, 2010a; Gerlai, 2010b; Norton, 2013; Piato et al., 2011; Stewart et al., 2014). Zebrafish may be of interest for chronic stress research as they express two glucocorticoid receptors (GR), GRα and GRβ, as humans do but not rodents (Schaaf et al., 2009; Schoonheim et al., 2010). GRβ has been associated with glucocorticoid resistance in humans, which is relevant for a number of diseases including major depression (Carvalho et al., 2014; Pace and Miller, 2009; Schoonheim et al., 2010; Silverman and Sternberg, 2012; Webster et al., 2001; Zhou and Cidlowski, 2005). Unpredictable chronic stress (UCS) impedes inhibitory avoidance learning in a single-trial inhibitory avoidance paradigm in the AB zebrafish strain (Piato et al., 2011). In this paradigm, fish learn to avoid swimming from a white to a black compartment to avoid an electric shock (Blank et al., 2009; Ng et al., 2012). Recently, we studied the effects of different shock intensities on inhibitory avoidance learning in an in-house-reared Tuebingen long-fin (TLF) zebrafish strain and showed associated changes in the regulation of a number of genes involved in anxiety, fear, learning and memory when measured 2 h following the task, including *grα* (Manuel et al., 2014). In rats it has been shown that UCS has a stronger impact on physiology and behaviour when given during the resting phase than during the active (or awake) phase (Aslani et al., 2014). Zebrafish are active during the daytime and rest during the night-time (Hurd et al., 1998). Disturbances during the night-time may negatively impact zebrafish behaviour (Löhr and Hammerschmidt, 2011; Singh et al., 2013). We therefore studied the effects of daytime and night-time UCS on inhibitory avoidance learning, whole-body cortisol content and gene expression levels, notably of *grα* and *grβ*, in TLF zebrafish to further assess the usefulness of zebrafish as an animal model in research related to chronic stress.

To induce UCS we modified an earlier published UCS protocol (Piato et al., 2011) to a milder regime to prevent exhaustion interfering with avoidance learning (Piato et al., 2011). We administered UCS for 7 or 14 days during the daytime (the 7 days/14 days UCS groups). We predicted that 14 days of UCS would reduce inhibitory avoidance learning, increase whole-body cortisol content and change the expression of associated genes (see next paragraph) more strongly than 7 days of UCS would. We also applied the UCS protocol during the night-time for 7 nights (the 7 nights UCS group). We predicted that the UCS protocol applied during the night-time would have a stronger impact compared with application during the active phase [based on studies on rats (Aslani et al., 2014)]. Further, we extended our inhibitory avoidance protocol (Manuel et al., 2014) with a second training session as multiple training sessions may improve the learning performance of zebrafish (Arthur and Levin, 2001; Williams et al., 2002). We therefore predicted that an additional training session would provide

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a better resolution of the effects of UCS on inhibitory avoidance learning.

As in an earlier study (Manuel et al., 2014), we assessed an array of genes in the telencephalon. Genes were selected on the basis of their relation to the stress response, anxiety and fear, as well as fear conditioning (de Kloet et al., 1999; Liu et al., 2004; Maximino et al., 2013; Upadhya et al., 2013) and include: *brain derived neurotrophic factor* (*bdnf*), *serotonin receptor 1ab* (*htr1ab*), *cocaine- and amphetamine-regulated transcript 4* (*cart4*), *corticotropin-releasing factor* (*crf*), *crf-binding protein* (*crf-bp*), *cannabinoid receptor 1* (*cnr1*), *grα*, *grβ* and *mineralocorticoid receptor* (*mr*). The telencephalon was specifically chosen for its involvement in learning and memory as well as fear and fear conditioning (lateral and medial zone of the dorsal pallium (Broglio et al., 2005; Mueller et al., 2011)). As many stress-related genes change their expression levels differentially in different parts of the brain, measuring gene expression in the telencephalon specifically provides a higher resolution compared with whole-brain analysis regarding the effects of UCS on inhibitory avoidance learning.

RESULTS

General observations

No mortality was observed as a result of the UCS protocol. Fish appeared healthy, were active in their home tanks and accepted food directly.

There were no fish that did not enter the black compartment on day 1. We observed no behavioural differences between groups during exposure to the shock: all groups showed erratic movements, seeking to escape or jumping out of the water when the shock was applied (Manuel et al., 2014). In addition, we did not observe any abnormal behaviour, such as periods of freezing behaviour (Kalueff et al., 2013), on any of the test days.

Inhibitory avoidance learning

Daytime UCS

To assess inhibitory avoidance learning, latency times of fish were recorded before training (day 1) and after training (day 2 and day 3; Fig. 1A). All fish entered the black compartment within 60 s on day 1, except one fish in the control group (80 s). Median latencies of groups ranged from 6 to 8 s. Mann–Whitney tests revealed no significant differences between groups (all $P \geq 0.16$).

Compared with day 1, the median latencies of all groups on day 2 significantly increased, but were notably strongest in the control group (all $P \leq 0.01$). Furthermore, compared with the control group, the 7 days UCS group did not have a lower median latency to enter the black compartment ($U=288.5$, $P=0.09$), while the 14 days UCS group had a significantly lower median latency ($U=328.5$, $P=0.003$). There was no difference between the 7 days UCS group and 14 days UCS group ($U=193$, $P=0.33$).

On day 3, the second shock led to an increase in the median latency in all groups, but only in the 7 days UCS group was this increase significant ($U=88$, $P=0.02$). The control group and 7 days UCS group showed no significant difference ($U=393.5$, $P=0.97$). However, the median latency of the 14 days UCS group remained significantly lower compared with the control group ($U=401.5$, $P=0.03$) but not compared with the 7 days UCS group ($U=162$, $P=0.08$).

Night-time UCS

To assess the effect of 7 nights of UCS on inhibitory avoidance learning, latency times of fish were recorded before training (day 1) and after training (day 2 and day 3; Fig. 1B). All fish entered the black compartment within 60 s on day 1, except for one fish in the control group (89 s) and one fish in the 7 nights UCS group (169 s). On day 1, the median latency of the control group was not significantly different from the median latency of the 7 nights UCS group ($U=153$, $P=0.18$).

Compared with day 1, the median latencies on day 2 were significantly increased in both the control group ($U=72.50$, $P=0.014$) and the 7 nights UCS group ($U=65.50$, $P<0.0001$). There was no

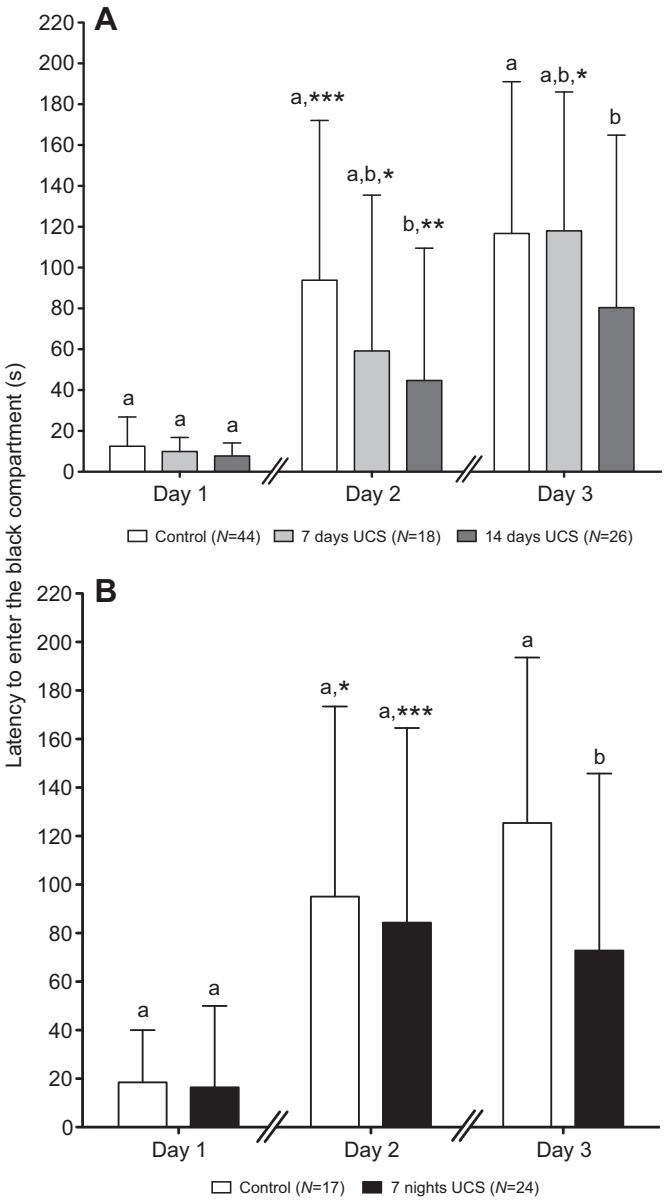

Fig. 1. Comparison of latency to enter the black compartment of zebrafish. Latency is shown for fish trained (A) under control conditions versus 7 or 14 days with unpredictable chronic stress (UCS) and (B) under control conditions versus 7 nights with UCS. For ease of reading, we have chosen to present bars reflecting the means + 1 s.d. rather than medians with interquartile ranges. Day 1 shows the initial latency recorded without training, whereas day 2 shows the latency after a single shock and day 3 after a second shock. Groups with different letters are significantly different from each other (one-way ANOVA for A, Mann–Whitney *U*-test for B; $P \leq 0.05$). Asterisks (*$P \leq 0.05$, **$P \leq 0.01$ and ***$P \leq 0.001$) indicate a significant increase in latency compared with the previous day only within a single treatment. *N*=number of fish.

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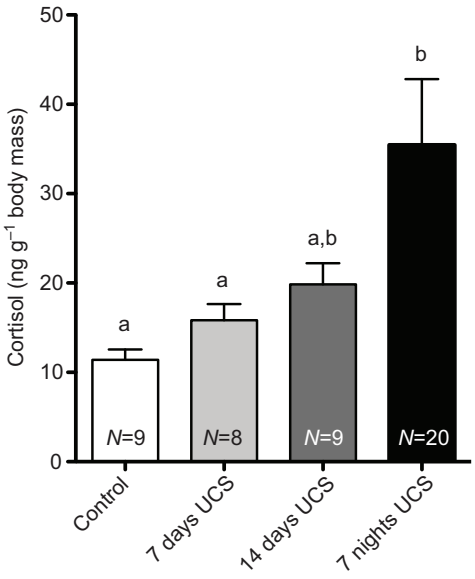

Fig. 2. Comparison of the whole-body cortisol content in the control group, the 7 days UCS group, the 14 days UCS group and the 7 nights UCS group. Bars represent group means + s.e.m. Groups with different letters are significantly different from each other (LSD *post hoc* analysis following a significant one-way ANOVA; $F_{3,42}$=3.125, P=0.04). N=number of fish.

significant difference between the median latencies of the control group and the 7 nights UCS group (U=203, P=0.99) on day 2.

On day 3, the second shock did not lead to a significant increase in median latency of the control group and the 7 nights UCS group when compared with day 2 (all $P \geq 0.24$). However, the median latency of the 7 nights UCS group was significantly lower than the median latency of the control group (U=130, P=0.04).

When compared with the latencies of the 7 days UCS group, we found that the latencies of the 7 nights UCS group were also significantly lower (U=140.5, P=0.05), while they did not differ from the 14 days UCS group (U=275.5, P=0.48) on day 3 (comparing day 3 of Fig. 1A,B).

Whole-body cortisol content

Fig. 2 shows the whole-body cortisol content for each group. The data show a gradual increase in cortisol level from controls (100%) to 7 days UCS (139%), to 14 days UCS (174%) to 7 nights UCS (231%). *Post hoc* analysis, following a significant one-way ANOVA (see Fig. 2), revealed that the 7 nights UCS group had significantly higher levels of whole-body cortisol content compared with the control group and the 7 days UCS group, but not compared with the 14 days UCS group. We observed no further statistically significant differences.

Gene expression analysis: daytime and night-time UCS

Fig. 3 shows the relative normalised gene expression profiles and *mr*/*grα* as well as *grβ*/*grα* ratios of the different groups. The figures exclude the following outliers as detected by Grubbs' test: one control subject for *cart4* (normalised expression 1.55); one 7 nights UCS subject for *htr1ab* (normalised expression 2.69) and one 7 days UCS subject for *cnr1* (normalised expression 1.48). For ease of reading, one-way ANOVA values and associated P-values are indicated in each panel. For *cart4* (Fig. 3A), we found that the 7 days UCS group had significantly higher levels of expression compared with the 7 nights UCS group and the control group, but not compared with the 14 days UCS group. For *htr1ab* (Fig. 3B), the 7 days UCS group had significantly higher levels of expression compared with the control group, the 14 days UCS group and 7 nights UCS group. For *crf-bp* (Fig. 3C) and *crf* (Fig. 3D), there were no significant differences in expression levels between groups. For *bdnf* (Fig. 3E) and *grβ* (Fig. 3F), the 7 nights UCS group had significantly higher levels of expression compared with the control group, the 7 days UCS group and the 14 days UCS group. For *cnr1* (Fig. 3G), following 14 days of UCS and 7 nights of UCS, we observed significantly higher levels of expression compared with the 7 days UCS group, but not compared with the control group. For *mr* (Fig. 3H), the 7 nights UCS group had significantly higher levels of expression compared with the control group, the 7 days UCS group and the 14 days UCS group. Expression of *grα* (Fig. 3I) was significantly higher in the 7 nights UCS group compared with the control group, the 7 days UCS group and the 14 days UCS group. There was no significant effect on the *mr*/*grα* ratio (Fig. 3J). The *grβ*/*grα* ratio (Fig. 3K) was significantly higher for the 7 nights UCS group compared with the control group, the 7 days UCS group and the 14 days UCS group.

Principal component analysis

We performed a principal component analysis (PCA) across the four different groups (control, 7 days UCS, 14 days UCS and 7 nights UCS). Although the Kayer–Meyer–Olkin (KMO) measure was moderate for this dataset (KMO=0.673), the Bartlett's test of sphericity indicated that the correlations between items were sufficiently large for PCA (χ^2=140.617, d.f.=45, P<0.0001). We extracted three components, which together explain 69.78% of variance (Table 1): *cart4*, *htr1ab*, *crf-bp* and *crf* loaded strongly on component 1; *bdnf*, *grβ*, *cnr1* and *mr* loaded strongly on component 2; *mr*, *grα*, *crf* and whole-body cortisol content loaded strongly on component 3. To assess the overall effect of these components, we ran a one-way ANOVA for each of these components. This revealed a weak main effect for component 1 ($F_{3,32}$=2.329, P=0.09). For component 2, a significant main effect was observed ($F_{3,32}$=10.060, P<0.001); *post hoc* analysis (least square differences, LSD) revealed that the 7 nights UCS group had significantly higher scores compared with the other three groups. No further statistical differences were observed. For component 3, a weak main effect was observed ($F_{3,32}$=2.808, P=0.06).

DISCUSSION

We assessed the effects of daytime and night-time UCS on inhibitory avoidance learning, whole-body cortisol levels and gene expression in an in-house-reared TLF zebrafish strain. Both 14 days and 7 nights of UCS resulted in poorer inhibitory avoidance learning compared with the control group. While whole-body cortisol content was moderately (but not significantly) increased in the 14 days UCS group, it significantly increased in the 7 nights UCS group. Only in the 7 nights UCS group was the expression of *bdnf*, *grβ*, *mr* and *grα* increased compared with the controls. In both the 14 days UCS and 7 nights UCS group, *cnr1* levels were increased compared with the 7 days UCS group. The 7 days of UCS treatment had only a small effect on learning and whole-body cortisol content, and this group showed increased expression levels of *cart4* and *htr1ab* compared with controls or 14 days of UCS and 7 nights of UCS.

Inhibitory avoidance learning

All fish tolerated the UCS protocol well, as we did not see any abnormal behaviour or mortality. Independently of the UCS protocol, all fish quickly entered the dark compartment on day 1, as

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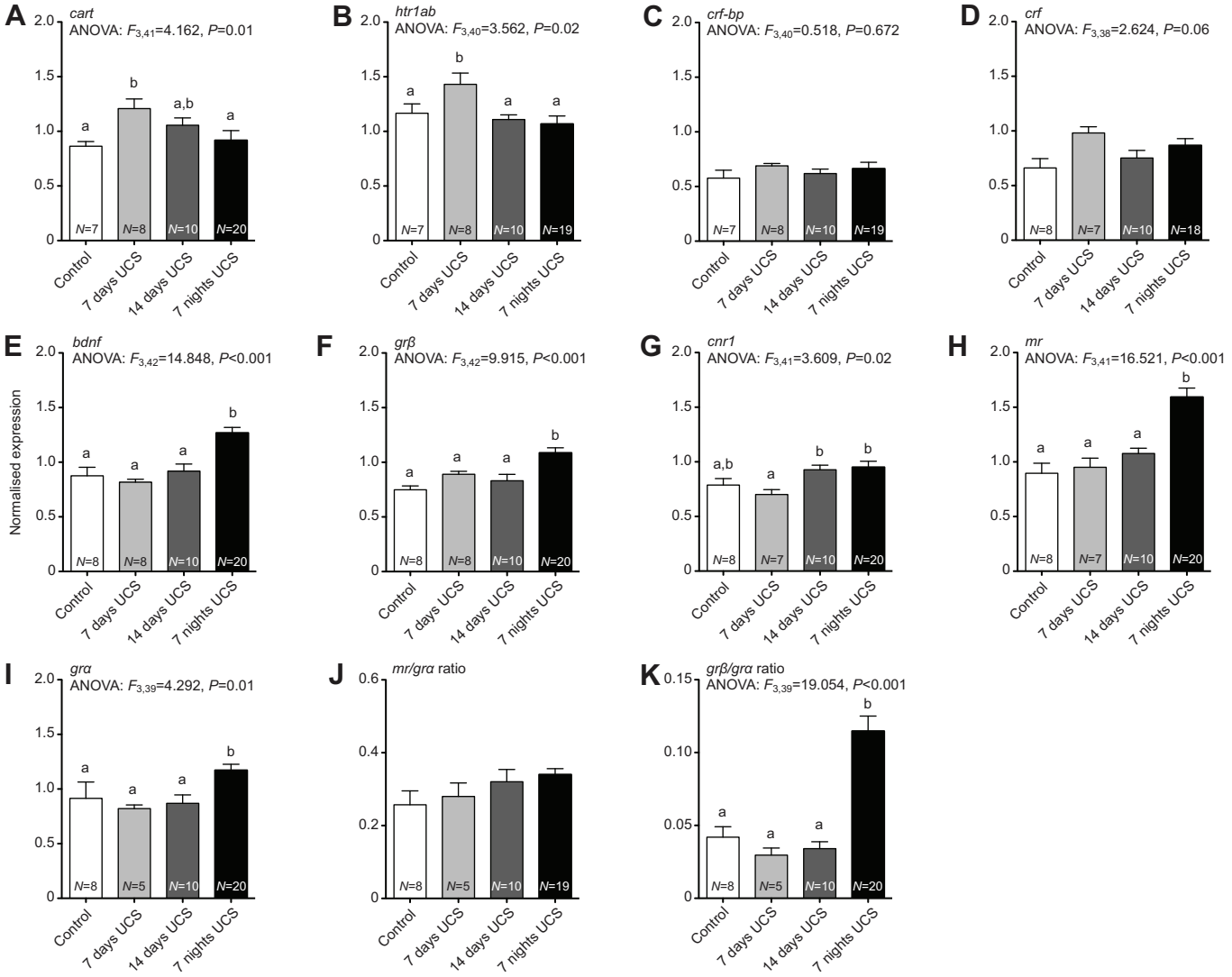

Fig. 3. Comparison of telencephalic gene expression in the control group, the 7 days UCS group, the 14 days UCS group and the 7 nights UCS group. Expression was normalised to that of elf1a/rpl13. Bars represent group means + s.e.m. Groups with different letters are significantly different from each other (LSD *post hoc* analysis following a significant one-way ANOVA; $P \leq 0.05$). *N*=number of fish. Note that J and K display ratios and not actual gene expression levels.

was their expected preference (Stephenson et al., 2011), showing that UCS had no effect on anxiety per se. The UCS protocol applied appeared to be effective as we observed a moderate (14 days) to strong (7 nights) increase in whole-body cortisol content, and poorer inhibitory avoidance learning following 14 days or 7 nights of UCS (Piato et al., 2011). Seven days of UCS only had minor effects on inhibitory avoidance learning and led to a small increase in whole-body cortisol content. These results are in line with our prediction that our UCS regime would have a strong effect after 14 days, but not after 7 days. Also in line with our prediction, the effects of UCS were stronger when given in the night-time than in the daytime: while we observed a minor effect in the 7 days UCS group on day 2, which disappeared on day 3, we observed a clear effect on day 3 in the 7 nights UCS group. Fish exposed to 7 days UCS significantly improved their performance on day 3, whereas those exposed to 7 nights UCS did not. Thus, extending the inhibitory avoidance protocol in time allowed for a more precise discrimination of UCS effects (Arthur and Levin, 2001; Williams et al., 2002).

Our data support earlier studies in zebrafish that showed that disturbances during the night negatively impact zebrafish behaviour (Löhr and Hammerschmidt, 2011; Singh et al., 2013). Furthermore, in rats, UCS during the resting phase has more impact than during the active phase (Aslani et al., 2014). Interestingly, in mice, repeated social defeat had a more pronounced negative outcome when applied during the active phase (Bartlang et al., 2012). Differences in inhibitory avoidance learning could be related to differences in responsiveness of the stress axis during the daytime and night-time. Studies in green sturgeon (*Acipenser medirostris*) (Lankford et al., 2003), sole (*Solea senegalensis*) (López-Olmeda et al., 2013) and the African catfish (*Clarias gariepinus*) (R.M., J. G. J. Boerrigter, M. Cloosterman, M.G., G.F., R.v.d.B. and H.v.d.V., unpublished data) have shown that the physiological responses (e.g. cortisol release) to a stressor are stronger during the resting phase compared with the active phase and that genes related to the stress axis are differently expressed. We suggest that this repeated stronger physiological response in addition to a (potential) disruption of the sleep–wake cycle may have caused the UCS protocol to impose a greater stress load, i.e. allostatic load (Korte et al., 2007), on the fish when applied during the night compared with the day.

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Table 1. Variables loaded onto components by a principal component analysis (PCA)

	Component 1 34.53%	Component 2 21.46%	Component 3 13.08%
cart4	**0.883**	0.059	–0.124
htr1ab	**0.827**	–0.224	–0.097
crf-bp	**0.637**	–0.149	0.105
bdnf	–0.193	**0.883**	–0.015
grβ	0.234	**0.799**	0.198
cnr1	–0.396	**0.681**	–0.049
mr	–0.240	**0.646**	**0.562**
grα	–0.132	0.008	**0.869**
crf	**0.461**	0.038	**0.781**
Cortisol	–0.335	0.350	**0.451**

Variables included: *brain derived neurotrophic factor* (*bdnf*), *glucocorticoid receptors α* (*grα*) and *β* (*grβ*), *mineralocorticoid receptor* (*mr*), *cocaine and amphetamine regulated transcript 4* (*cart4*), *serotonin receptor 1ab* (*htr1ab*), *corticotropin-releasing factor* (*crf*), *crf-binding protein* (*crf-bp*) and whole-body cortisol. Scores larger than 0.400 or smaller than −0.400 were accepted for loading on to a component and are shown in bold. This resulted in the loading of *cart4*, *htr1ab*, *crf-bp* and *crf* on to component 1; the loading of *bdnf*, *grβ*, *cnr1* and *mr* on to component 2; and the loading of *mr*, *grα*, *crf* and whole-body cortisol content on to component 3. Note that *crf* and *mr* were loaded on to two components. Percentages indicate the portion of variation explained by each component.

Gene expression

While we only observed minor effects on the expression levels of *crf* (P=0.06), the overall expression appeared to increase in the UCS groups, most notably in the 7 days UCS group (significant to control: P=0.01). This weak effect of UCS on *crf* expression seems at variance with the literature as *crf* expression has been shown to strongly increase following UCS (Chakravarty et al., 2013; Piato et al., 2011). The reasons underlying these differences may be related to sampling procedures: while we sampled the telencephalon specifically, others sampled the whole brain (Chakravarty et al., 2013; Piato et al., 2011). Expression of *crf* can be found in many different areas outside the telencephalon (Alderman and Bernier, 2007), areas that may differently respond to chronic stress. It has been shown in rats that in both the amygdala and hippocampus, two forebrain areas, ERK1/2 activity (an effector molecule in the actions of CRF) is decreased after 2 weeks of UCS but not after 4 weeks (Castro et al., 2012), a temporally differential effect akin to what we observed in our present study (7 days versus 14 days UCS). Thus, in the telencephalon, a short duration or lower stress load (7 days UCS) may lead to different adaptive changes than a longer duration or higher stress load (14 days UCS and 7 nights UCS) at the level of *crf* expression. As we took samples following the task, while others sampled independent of the task, our data may also reflect an interaction between the UCS protocol and the task, rather than effects of UCS per se. Thus, it is possible that the changes in *crf* expression which we observed are not solely related to UCS. At least for the 7 days UCS group, the *crf* increase observed here may be related to learning and memory (Radulovic et al., 1999) as there was a significant improvement in avoidance learning on day 3 compared with day 2. In support of this, expression levels of *htr1ab* (Ögren et al., 2008) and *cart4* (Upadhya et al., 2011; Yermolaieva et al., 2001), shown to be involved in learning and memory as well, also significantly increased in the 7 days UCS group. This hypothesis is strengthened by the loading of these genes (along with *crf-bp*, which probably follows the expression pattern of *crf*) onto the same component in the PCA.

Following 7 nights of UCS, we found increased expression levels of *grα*, *grβ*, *mr*, *bdnf* and *cnr1*. Interestingly, *grβ*, *mr*, *bdnf* and *cnr1* loaded onto the same component in the PCA. In our earlier experiments, concerning the effects on inhibitory avoidance learning of different shock intensities, *grβ* and *bdnf* also loaded onto the same component (Manuel et al., 2014), supporting the present data. The loading of these genes onto a single component, and their similar changes following 7 nights of UCS, suggest that they may be associated in the context of a high stress load as deduced from the strong increase in whole-body cortisol following 7 nights of UCS. While most studies in rodents show that chronic stress decreases expression of *bdnf* (Suri and Vaidya, 2013), an increase in *bdnf* following UCS is not unprecedented for zebrafish (Chakravarty et al., 2013). Interestingly, it has been suggested that activation of MR or GRα may have different effects on BDNF: while MR activation stimulates *bdnf* expression, GRα activation decreases *bdnf* expression (Suri and Vaidya, 2013). Accordingly, the increase in *bdnf* expression in our present study may be a result of a stronger increase in *mr* than *grα* expression, which is supported by the increased *mr*/*grα* ratio following 7 nights of UCS (P=0.02, versus control). Under basal conditions, telencephalic MR is fully occupied with maintaining basal neuronal activity (Reul and de Kloet, 1985); an increased level of *mr* and *grα*, and the accompanying increase in *bdnf* expression following 7 nights of UCS may be a means to maintain neuronal integrity under chronic stress. It has indeed been suggested that an increase in *bdnf* is a compensatory mechanism that allows the development of an inhibitory phenotype by contributing to the upregulation of inhibitory mechanisms (McMillan et al., 2004). The increased expression of *grβ* also seems to be in line with these protective changes as it has been suggested that GRβ exerts a dominant-negative activity over GRα (Schoonheim et al., 2010). Increased expression levels of *grβ* could therefore be a mechanism to protect the brain against chronic elevated glucocorticoid exposure. This hypothesis is supported by the observed increase in the *grβ*/*grα* ratio in the 7 nights UCS group, which is indicative of a stronger increase in the expression of *grβ* compared with *grα*. However, this increase in *grβ* is suggested to be mediated by pro-inflammatory cytokines (Webster et al., 2001) and may lead to glucocortiocoid resistance associated with several diseases, among them major depression (Carvalho et al., 2014; Zhou and Cidlowski, 2005). Thus, the present data raise the question of the extent to which the observed effects are indicative for liability of disease in our 7 nights UCS subjects. It is clear that this warrants further studies.

For *cnr1*, we observed an increased expression in the 14 days and 7 nights UCS groups when compared with the 7 days UCS group. Studies in rodents have shown the involvement of the endocannabinoid system in the regulation of the stress response during chronic stress and recovery (Gorzalka et al., 2008; Hill et al., 2011; Lee and Hill, 2013). For example, CB1 (CNR1 in zebrafish) was down-regulated in the rat hippocampus during chronic stress, while it was up-regulated during the recovery period (Lee and Hill, 2013). As we measured gene expression 3 days after terminating the UCS protocol, the effects we observed may be due to up-regulation during the recovery period. The lack of increase in the 7 days UCS group may reflect that these fish have already recovered as suggested by their avoidance learning. Further studies focusing on chronic stress and CNR1 in zebrafish seem warranted. Studies on mammals have also shown that CB1 is associated with pain and pain perception, where activation of CB1 reduces pain sensitivity (Fine and Rosenfeld, 2013; Guindon and Hohmann, 2009; Wilson and Nicoll, 2002). Higher levels of CNR1 could contribute to poorer inhibitory avoidance learning as the paradigm is based on a potentially noxious stimulus (i.e. electric shock), although, as indicated, we did not see any differences in the behavioural response to receiving the shock.

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We observed that *mr*, *grα*, *crf* and whole-body cortisol content loaded onto the same component in the PCA. Previously, we also found that *mr* and *grα* loaded onto the same component (Manuel et al., 2014) strengthening our current observation. MR is involved in the early stages of stress-related changes, while GRα is key in long-term changes and normalisation following stress (de Kloet et al., 2005; Joëls et al., 2007). Still, our data suggest a relationship between these receptors in our experiments [without stress (Manuel et al., 2014) and with stress (reported here)]. Thus, this relationship may also be the result of an interaction of the UCS with the task, as both MR and GR are involved in learning and memory (Cerqueira et al., 2005; ter Horst et al., 2012; Lupien and McEwen, 1997; Zhou et al., 2010). The relative balance between these receptors affects memory in adults and changes in the *mr*/*grα* ratio have been associated with decreased learning and memory (de Kloet et al., 1999; Lupien and Lepage, 2001). Previous studies have shown that chronic stress in zebrafish increases the *mr*/*grα* ratio (Pavlidis et al., 2011). Although we did not find a strong overall effect on the *mr*/*grα* ratio here, we did see a steady increase in this ratio with increasing stress load (reflected by whole-body cortisol content). This may have contributed to the decrease in avoidance learning, which is supported by the fact that we did see a significantly higher *mr*/*grα* ratio when comparing the 7 nights UCS group with the control group specifically (P=0.02). These results warrant further studies focusing on the *mr*/*grα* ratio and how this is involved in learning and memory in zebrafish.

Putative mechanisms

Several mechanisms may be proposed to underlie the effects of chronic stress on avoidance learning. First, chronic stress may change the appraisal of the shock. In rodents, chronic stress has been shown to increase anxiety and fear conditioning, accompanied by changes in synaptic activity in the amygdala (Roozendaal et al., 2009), which find their homologue in the medial zone of the dorsal pallium of the teleostean telencephalon (Mueller et al., 2011). We did not observe differences between groups on day 1 (latency to enter the dark compartment; anxiety) nor differences between groups concerning their behavioural response to receiving the shock. Moreover, we observed decreased rather than increased avoidance learning, making chronic stress-induced hypersensitivity in sensory processing or appraisal unlikely in our study. Second, increased levels of cortisol may lead to atrophy, decreased proliferation and changes in synaptic meta-plasticity in the dorsal zone of the lateral pallium (the teleostean homologue of the hippocampus) as has been described for the rat hippocampus (de Kloet et al., 1999; Krugers et al., 2010; Lynch, 2004; Magariños and McEwen, 1995; McEwen, 2005; Yan et al., 2011). The hippocampus plays an important role in the formation and retrieval of memory related to contextual fear learning (Wiltgen et al., 2006), but not cue learning (Olvera-Cortés et al., 2002). Context and place learning are likely to underlie our paradigm, as we did not use an explicit cue to signal the shock (Aoki et al., 2013; Sison and Gerlai, 2010; Xu et al., 2007). Accordingly, the dorsal zone of the lateral pallium may be affected, and this could have disrupted contextual shock learning. Future studies should determine this in greater detail.

Limitations

We measured gene expression levels following inhibitory avoidance. We reasoned that differences in gene expression between the control group and UCS groups would be closely associated with differences in inhibitory avoidance learning between the control group and UCS groups. We did not aim to optimise the time point of sampling to detect the effects of inhibitory avoidance learning on gene expression. We therefore only measured gene expression levels at a single time point: 2 h following inhibitory avoidance. This time window was chosen based on a study by Morsink and colleagues (Morsink et al., 2006), who showed that between 1 and 3 h following a challenge a sufficient number of genes show changes in expression. Future studies may therefore examine the temporal dynamics of gene expression following testing, combined with analyses prior to inhibitory avoidance learning. This could also include the analysis of gene expression in separate regions of the telencephalon rather than the whole telencephalon (Aoki et al., 2013). The effects on gene expression levels that we observed should therefore currently be regarded as a starting point for subsequent research rather than as conclusive evidence.

Concluding remarks

Reproducibility of results within and between laboratories is crucial for advancing the field of behaviour and genetics (Crabbe et al., 1999; Mandillo et al., 2008; Wahlsten et al., 2006). The zebrafish is a relatively new model in genetics and brain–behaviour research and differences between strains of zebrafish (Egan et al., 2009; Vignet et al., 2013; Wahlsten et al., 2006) as well as rearing conditions within and between laboratories (Mahabir et al., 2013; Parker et al., 2012; Pavlidis et al., 2013) may affect the outcome of experiments. Our data strongly suggest that at a behavioural and physiological level the UCS protocol is robust and reproducible in decreasing inhibitory learning and elevating whole-body cortisol content across strains of zebrafish, i.e. the TLF strain used in our study and the AB strain in the study of Piato and colleagues (Piato et al., 2011), which is critical for advancing the zebrafish as a model for brain–behaviour studies associated with depression, anxiety and other mood-related disorders (Chakravarty et al., 2013; Gerlai, 2010a; Gerlai, 2010b; Norton, 2013; Piato et al., 2011). In addition, our data reveal that the reduction in inhibitory avoidance learning relates to increasing levels of stress load. However, only after a strong stress load (i.e. 7 nights of UCS) did we observe clear changes in telencephalic gene expression. These observations offer a selection of candidate genes (e.g. *bdnf*, *mr*, *grβ* and *cnr1*) to be studied in more detail in future work.

MATERIALS AND METHODS

Ethical approval

Experimental procedures were approved by the ethical committee of Wageningen UR (DEC: 2012010.b) and were conducted in accordance with Dutch laws (national legislation Wet op de Dierproeven 1996) and European regulations (Directive 86/609/ EEC).

Animals and housing

The fish used for this experiment were an in-house-reared TLF zebrafish strain. Fish were a mix of offspring from two parental couples and hatched within the same week. At the age of 12 months, 132 animals (a mix of males and females) were pooled and randomly assigned to 33 aquaria (2 l volume, four fish per tank). Three animals died during the acclimation period (8 weeks), resulting in 129 animals in the experiment. Fish used for the 7 nights UCS treatment were acclimated to the new photoperiod for 8 weeks prior to the start of the stress protocol. Each aquarium received an artificial floating plant and was provided with independent water in- and out-flow (Nijmegen tapwater: 26°C, pH 8.0, 400 µS cm^{-1}); inflow water had passed through a biological filter (300 l volume). The daytime UCS group was kept under a photoperiod of 12 h light:12 h dark (lights on from 07:00 h to 19:00 h) with feeding at 09:00 h (artemia) and 15:00 h (TetraMin, Tetra, Melle, Germany). The night-time UCS group was kept on an adjusted photoperiod of 12 h light:12 h dark (lights on from 12:00 h to 24:00 h) with feeding at 13.00 h (artemia) and 18:00 h (TetraMin).

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Experimental groups

Six experimental groups were used in the experiment. For practical reasons, the night-time control and UCS fish were kept on a different photoperiod. The daytime group consisted of four experimental groups: two daytime control groups (N=22 each), one 7 days UCS group (N=18) and one 14 days UCS group (N=26). To control for the occurrence of changes in learning behaviour over the course of the experiment and to replicate the data of the (first) control group, we included a second control group at the end of the experiment. These groups did not show statistical differences in avoidance behaviour and, for this specific parameter, data were therefore pooled (N=44). Only the first group was used for whole-body cortisol content and gene expression analysis. The night-time group consisted of two experimental groups: a night-time control group (N=17) and a 7 nights UCS group (N=24). The night-time controls served to control for possible differences caused by the shift in photoperiod and potential effects related to the time of testing, i.e. inhibitory avoidance learning was assessed at 11.00 h for the daytime groups (4 h after lights on) and at 15:00 h for the night-time groups (3 h after lights on).

UCS protocol

To induce UCS, a previously published protocol was modified to a milder regime in order to prevent exhaustion, which confounds avoidance learning (Piato et al., 2011). Briefly, for a total of 7 days, 14 days or 7 nights (Fig. 4A), fish were subjected twice daily, at random times to a chosen challenge. All fish were given the same stressor at the same moment. Stressors included: rapidly (within1 min) heating the tank water up to 33°C for 30 min; rapidly (within 1 min) cooling the tank water down to 23°C for 30 min; crowding of 20 fish for 60 min in a 500 ml glass beaker; netting stress for 30 min; lowered water levels (dorsal part of the body was air-exposed) for 15 min; three consecutive (biofiltered) water replacements with fish in their tank (i.e. fish and water were poured into a net, fish were returned to the aquarium and water was replenished); chasing fish for 2×5 min with a net (15 min rest in between); air-exposure for 3×1 min (5 min rest in between); and fasting for 24 h. Following some of the stressors (e.g. crowding), fish were randomly divided into new groups of four, giving an additional, social, stressor.

Inhibitory avoidance protocol

For inhibitory avoidance learning, a previously described protocol was used (Blank et al., 2009; Manuel et al., 2014) with one modification: not one shock but two were given (see Fig. 4B). In short, an aquarium (60×30×30 cm; 10 cm water level) was split into two equal compartments, separated by a manually operated sliding door. The surfaces of one compartment were white while the surfaces of the other compartment were black. Compartments were not covered by a lid and light was measured at 350 lx at the surface of the water. The black compartment contained two metal plates (covered with black sound box mesh to prevent light reflection by the metal) that covered two opposite walls completely. Both plates were wired to a power source, which allowed 3 V AC to be put between the plates in the water (measured at the middle of the tank, across a distance of 15 cm between electrodes). Inhibitory avoidance learning was assessed for each fish individually (i.e. not as a group).

On day 1, a fish was placed in the white compartment with the sliding door closed. After 60 s of acclimation, the sliding door was lifted, giving the fish free access to the black compartment. As is their natural tendency, zebrafish will readily enter the black compartment when given this option (Stephenson et al., 2011). Once the fish had completely entered the black compartment, the sliding door was closed and an electric shock (3 V AC) was given for 5 s, after which the fish was returned to its home tank. Fish that would not enter the black compartment within 180 s were excluded from further experimentation. For each fish, the latency time to enter the black compartment was recorded. Higher latencies indicate that animals are less anxious in the white compartment.

On day 2, the procedure was repeated. After 60 s, the sliding door was opened and the fish was given 180 s to make a choice to enter the black

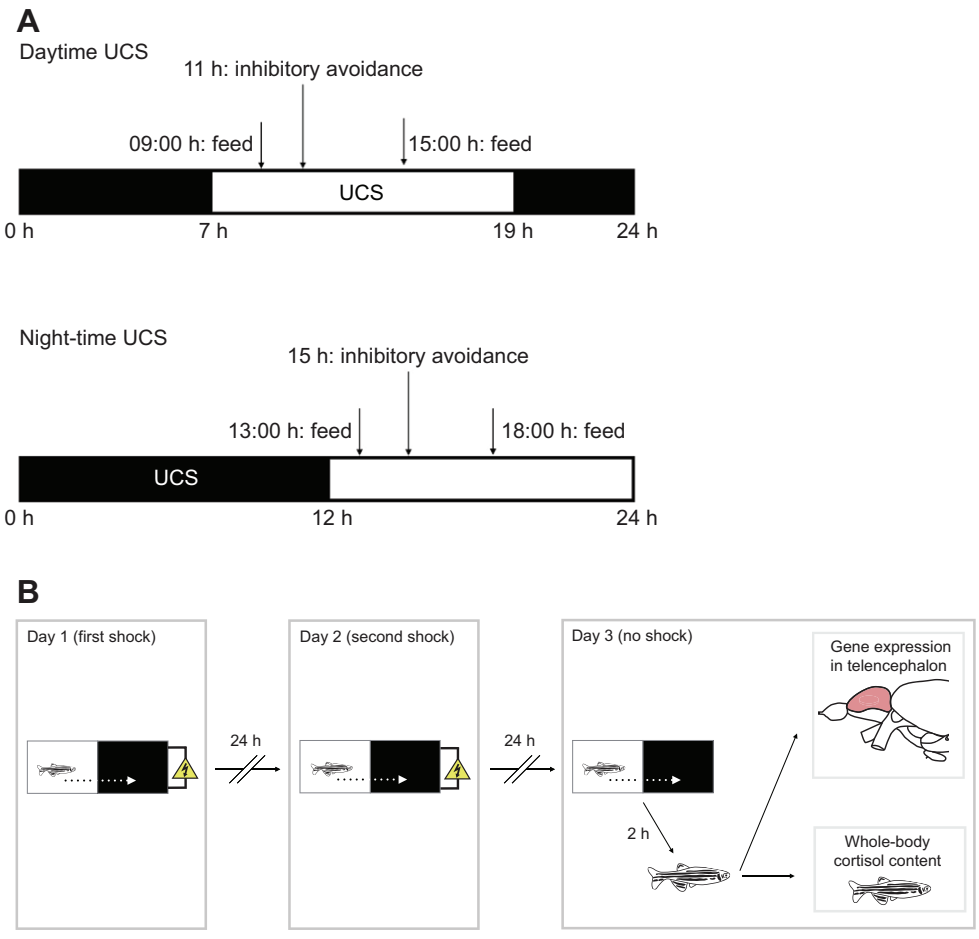

Fig. 4. Schematic overview of the housing photoperiods and the inhibitory avoidance learning protocol. (A) The two different photoperiods used for the daytime UCS and night-time UCS. Indicated are the phase in which UCS was applied and the times for feeding and inhibitory avoidance learning. (B) On day 1, fish were trained in the inhibitory avoidance protocol by receiving a shock upon entering the dark compartment. On day 2, fish were assessed for inhibitory avoidance learning. Fish were selected on the basis of their behaviour: non-avoider (<60 s latency) and avoider (≥180 s latency). The 2 h post-inhibitory avoidance fish were sampled for assessment of telencephalic (indicated in red) gene expression (*brain derived neurotrophic factor*, *bdnf*; *glucocorticoid receptors α* and *β*, *grα* and *grβ*; *mineralocorticoid receptor*, *mr*; *cocaine and amphetamine regulated transcript*, *cart*; *serotonin receptor 1ab*, *htr1ab*; *corticotropin-releasing factor, crf*; and *crf-binding protein*, *crf-bp*) and whole-body cortisol content.

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compartment or not. When the fish entered the black compartment within this time window, a second shock was given. Fish that did not enter within 180 s were carefully driven into the black compartment with a small net and then received the second shock. This was done to give all fish the same number of shocks. For each fish, the latency to enter the black compartment was recorded. Higher latencies are indicative of increased avoidance learning.

On day 3, fish were again placed within the white compartment. After 60 s, the sliding door was opened and the fish were given 180 s to choose to enter the black compartment or not. This time, when the fish entered the black compartment, no shock was given and fish that did not enter within 180 s were not driven into the black compartment. Then, fish were taken out of the experiment and killed 2 h after the test (see 'Tissue collection and preparation'). For each subject, the latency to enter the black compartment was recorded. Higher latencies are indicative for increased avoidance learning.

Operation of the sliding door was done manually and visual observations were made in real-time and recorded on-site. Recording of the latency time was done by hand using a stopwatch. One experimenter (R.M.) recorded all latencies. All procedures were carried out in a manner that caused the least possible disturbance to fish during the experiment.

Tissue collection and preparation

As indicated above (see 'Inhibitory avoidance protocol'), on the third day of the inhibitory avoidance protocol, tissues were collected 2 h after the test (Manuel et al., 2014). Not all fish were used for whole-body cortisol content and gene expression analysis, as some were used for other purposes (e.g. *in situ* hybridisation; not reported here). For each group, 8–10 fish were randomly taken. Time of sampling was chosen based on a study by Morsink and colleagues (Morsink et al., 2006), showing that between 1 and 3 h post-challenge a sufficient number of non-immediate early genes respond. Anaesthesia was given by placing fish from each group in water containing 2-phenoxyethanol (0.1% v/v). Once deeply anaesthetised (within 30 s), the telencephalon was dissected out, snap-frozen in liquid nitrogen and stored at −80 °C until further analysis. The remains of the fish were collected and stored at −80°C until whole-body cortisol content analysis (see 'Whole-body cortisol content').

Whole-body cortisol content

To evaluate stress levels as a result of the UCS protocol followed by the inhibitory avoidance paradigm, we assessed whole-body cortisol content. Zebrafish (previously stored at −80°C; see 'Tissue collection and preparation') were thawed on ice and homogenised individually in 1 ml PBS (80 mmol l^{-1} Na_2HPO_4, 20 mmol l^{-1} NaH_2PO_4, 100 mmol l^{-1} NaCl, pH 7.4) with a microblender. The homogenate was then mixed with 4 ml methanol (J. T. Baker, Deventer, The Netherlands) and left at 4°C for 1 h. Subsequently, the mixture was centrifuged (4°C, 3000 ***g***, 5 min) and the supernatant was collected. The pellet was resuspended in 4 ml methanol and left at 4°C for 30 min followed by centrifugation and collection of the supernatant (this step was repeated twice). The collected methanol (16 ml) was evaporated under N_2 gas, leaving a residue film containing steroids, which was reconstituted in 200 µl radioimmunoassay buffer (100 mmol l^{-1} Tris, 0.9% NaCl, 0.1% 8-anilino-1-naphthalenesulphonic acid, 0.02% NaN_3).

Cortisol was measured as previously described (Gorissen et al., 2012). Briefly, 96-well microtitre plates were coated with mouse monoclonal (XM210) cortisol-antibodies (Abcam, Cambridge, MA, USA) in coating buffer. Plates were cleared of coating buffer and washed before blocking possible non-specific binding sites with blocking buffer. Wells were cleared of blocking buffer and 10 µl of standard or sample, together with 90 µl of ^{3}H-cortisol tracer, was added to designated wells. Non-specifics received assay buffer (10 µl) and tracer only. After the incubation period, wells were cleared and washed before scintillation liquid was added and radioactivity measured with a β-counter (detection limit: 4 ng ml^{-1}; inter-assay VC: 12.5% and intra-assay VC: 2.5%). Cross-reactivity with other relevant steroids was considered insignificant (less than 1% at 50% cortisol saturation).

Gene expression analysis

Genes analysed were *bdnf*, *htr1ab*, *cart4*, *crf*, *crf-bp*, *cnr1*, *grα*, *grβ* and *mr*. Two internal standards [*ribosomal protein L13* (*rpl13*) and *elongation factor 1α* (*elf1α*)] were used for normalisation. Primer sequences are shown in Table 2.

Total RNA was isolated using Trizol (Invitrogen, Carlsbad, CA, USA) according to the manufacturer's instructions, including an additional precipitation step with ethanol and sodium acetate. RNA concentration and purity were measured by nanodrop spectrophotometry. Genomic DNA was removed by treatment with DNase I (Invitrogen) as follows: 1 µl of DNase I (1 U $µl^{-1}$) and 1 µl DNase I reaction buffer (10×) were added to 8 µl total RNA (500 ng) and incubated in a total volume of 10 µl at room temperature for 15 min. Subsequently, DNase was inactivated by addition of 1 µl EDTA (25 mmol l^{-1}) and incubation for 10 min at 65°C. Next, each sample received 1 µl random primers (250 ng $µl^{-1}$), 4 µl First Strand buffer (5×), 1 µl dNTP mix (10 mmol l^{-1}), 1 µl DTT (0.1 mol l^{-1}), 1 µl RNaseOUT (10 U) and 0.5 µl Superscript II Reverse Transcriptase (100 U $µl^{-1}$) (all from Invitrogen) and incubated at 25°C for 10 min, followed by 50 min at 42°C and finally 15 min at 70°C. Afterwards, cDNA was diluted 5 times with ultra-pure water and stored at −20°C until analysis. Relative gene expression was assessed by real-time qPCR. Briefly, 4 µl of cDNA was used as a template in a reaction with 10 µl iQ SYBR Green Supermix (Bio-Rad, Hercules, CA, USA), 0.8 µl forward and reverse primer each (10 µmol l^{-1}; Table 2) and 4.4 µl ultra-pure water. qPCR (3 min 95°C, 40 cycles of 15 s at 95°C and 1 min at 60°C) was carried out on a CFX 96 (Bio-Rad) qPCR machine. Data were analysed with the ΔΔCt-method, corrected for primer efficiency and normalised for two house-keeping genes (see Vandesompele et al., 2002).

As the ratio of *mr*/*grα* has been used as an indicator for the stress load of subjects (de Kloet et al., 1999; Lupien and Lepage, 2001), we calculated this ratio from the gene expression data using the normalised (i.e. non-relative) expression levels. We also calculated the *grβ*/*grα* ratio as this may indicate the extent to which the expression of the different isoforms of *gr* changes as a function of stress load (Stolte et al., 2008).

Table 2. Nucleotide sequences of the forward and reverse primers used for qPCR

Gene	Accession no.	Forward primer	Reverse primer
elf1α	AY422992	CTGGAGGCCAGCTCAAACAT	TCAAGAAGAGTAGTACCGCTAGCATTAC
rpl13	NM_212784	TCTGGAGGACTGTAAGAGGTATGC	AGACGCACAATCTTGAGAGCAG
bdnf	NM_131595	AGAGCGGACGAATATCGCAG	GTTGGAACTTTACTGTCCAGTCG
grα	EF436284.1	ACTCCATGCACGACTTGGTG	GCATTTCGGGAAACTCCACG
grβ	EF436285.1	GATGAACTACGAATGTCTTA	GCAACAGACAGCCAGACAGCTCACT
mr	NM_001100403	CTTCCAGGTTTCCGCAGTCTAC	GGAGGAGAGACACATCCAGGAAT
cart4	NM_001082932	GCTGAGGCACTCGATGAACT	GAAGAAAGTGTTGCAGGCGG
htr1ab	NM_001145766	GGACATTAAAACGCGCTGCT	ATGCAAGTCTTGGGTTGAGACT
cnr1	NM_212820	TACATCCTCTGGAAGGCCCA	GGGGGTCTGCACCTTTGTG
crf	BC164878	CGAGACATCCCAGTATCCAAAAAG	TCCAACAGACGCTGCGTTAA
crf-bp	NM_001003459	ACAATGATCTCAAGAGGTCCAT	CCACCAAGAAGCTCAACAAA

Elongation factor 1α (*elf1α*) and *ribosomal protein L13* (*rpl*13) were used as housekeeping genes. Genes of interest were *brain derived neurotrophic factor* (*bdnf*), *glucocorticoid receptors α* (*grα*) and *β* (*grβ*), *mineralocorticoid receptor* (*mr*), *cocaine and amphetamine regulated transcript* 4 (*cart4*), *serotonin receptor 1ab* (*htr1ab*), *corticotropin-releasing factor* (*crf*) and *crf-binding protein* (*crf-bp*).

Statistical analysis

Statistical analyses were performed with IBM SPSS Statistics 21 for Mac (IBM, Armonk, NY, USA). Data were plotted with GraphPad Prism 5.0 for Mac (GraphPad Software Inc., La Jolla, CA, USA).

As we introduced a cut-off point of 180 s, differences in latency times between groups were analysed with non-parametric tests: a Kruskal–Wallis test (followed by pair-wise comparisons) and a Mann–Whitney *U*-test for within-group analysis between day 1 and day 2, and day 2 and day 3, as we could not individually label the fish, which prevented pair-wise analyses.

Data for whole-body cortisol content and gene expression were subjected to Grubbs' test for outliers (extreme studentised deviate) using a stringent criterion (α=0.01). Changes in whole-body cortisol content and telencephalic gene expression were analysed using a one-way ANOVA. *Post hoc* testing following significance was done by a least square differences (LSD) *post hoc* test (Ferguson, 1981).

To assess inter-relationships between gene expression levels and whole-body cortisol content, we conducted a PCA with orthogonal rotation (varimax with Kaiser normalisation). In the case of missing samples, data were excluded list-wise. The number of components to retain was based on their eigenvalue (>1) and a visual inspection of the scree plot. Additionally, the KMO measure of sampling adequacy and Bartlett's test of sphericity were run to ensure that the data obeyed analysis criteria. Component scores were saved and used for further analysis. The component loading cut-off point was −0.400 or 0.400 (Ferguson, 1981).

In all cases, significance was accepted when $P \leq 0.05$ (two-tailed) unless otherwise stated (i.e. adjusted α in the case of multiple comparisons).

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Competing interests

The authors declare no competing financial interests.

Author contributions

R.M., M.G., L.O.E.E., H.v.d.V., G.F. and R.v.d.B. conceived and designed the experiments; R.M., M.G. and J.Z. carried out the experiments and data acquisition; R.M., M.G. and R.v.d.B. analysed and interpreted the data; R.M. and R.v.d.B. drafted the manuscript; M.G., J.Z., L.O.E.E., H.v.d.V. and G.F. critically revised the manuscript:

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References

Alderman, S. L. and Bernier, N. J. (2007). Localization of corticotropin-releasing factor, urotensin I, and CRF-binding protein gene expression in the brain of the zebrafish, *Danio rerio*. *J. Comp. Neurol.* **502**, 783-793.

Aoki, T., Kinoshita, M., Aoki, R., Agetsuma, M., Aizawa, H., Yamazaki, M., Takahoko, M., Amo, R., Arata, A., Higashijima, S. et al. (2013). Imaging of neural ensemble for the retrieval of a learned behavioral program. *Neuron* **78**, 881-894.

Arthur, D. and Levin, E. (2001). Spatial and non-spatial visual discrimination learning in zebrafish (*Danio rerio*). *Anim. Cogn.* **4**, 125-131.

Aslani, S., Harb, M. R., Costa, P. S., Almeida, O. F. X., Sousa, N. and Palha, J. A. (2014). Day and night: diurnal phase influences the response to chronic mild stress. *Front. Behav. Neurosci.* **8**, 82.

Bartlang, M. S., Neumann, I. D., Slattery, D. A., Uschold-Schmidt, N., Kraus, D., Helfrich-Förster, C. and Reber, S. O. (2012). Time matters: pathological effects of repeated psychosocial stress during the active, but not inactive, phase of male mice. *J. Endocrinol.* **215**, 425-437.

Blank, M., Guerim, L. D., Cordeiro, R. F. and Vianna, M. R. M. (2009). A one-trial inhibitory avoidance task to zebrafish: rapid acquisition of an NMDA-dependent long-term memory. *Neurobiol. Learn. Mem.* **92**, 529-534.

Broglio, C., Gómez, A., Durán, E., Ocaña, F. M., Jiménez-Moya, F., Rodríguez, F. and Salas, C. (2005). Hallmarks of a common forebrain vertebrate plan: specialized pallial areas for spatial, temporal and emotional memory in actinopterygian fish. *Brain Res. Bull.* **66**, 277-281.

Carvalho, L. A., Bergink, V., Sumaski, L., Wijkhuijs, J., Hoogendijk, W. J., Birkenhager, T. K. and Drexhage, H. A. (2014). Inflammatory activation is associated with a reduced glucocorticoid receptor alpha/beta expression ratio in monocytes of inpatients with melancholic major depressive disorder. *Transl. Psychiatry* **4**, e344.

Castro, J. E., Diessler, S., Varea, E., Márquez, C., Larsen, M. H., Cordero, M. I. and Sandi, C. (2012). Personality traits in rats predict vulnerability and resilience to developing stress-induced depression-like behaviors, HPA axis hyper-reactivity and brain changes in pERK1/2 activity. *Psychoneuroendocrinology* **37**, 1209-1223.

Cerqueira, J. J., Catania, C., Sotiropoulos, I., Schubert, M., Kalisch, R., Almeida, O. F., Auer, D. P. and Sousa, N. (2005). Corticosteroid status influences the volume of the rat cingulate cortex - a magnetic resonance imaging study. *J. Psychiatr. Res.* **39**, 451-460.

Chakravarty, S., Reddy, B. R., Sudhakar, S. R., Saxena, S., Das, T., Meghah, V., Brahmendra Swamy, C. V., Kumar, A. and Idris, M. M. (2013). Chronic unpredictable stress (CUS)-induced anxiety and related mood disorders in a zebrafish model: altered brain proteome profile implicates mitochondrial dysfunction. *PLoS ONE* **8**, e63302.

Crabbe, J. C., Wahlsten, D. and Dudek, B. C. (1999). Genetics of mouse behavior: interactions with laboratory environment. *Science* **284**, 1670-1672.

de Kloet, E. R., Oitzl, M. S. and Joëls, M. (1999). Stress and cognition: are corticosteroids good or bad guys? *Trends Neurosci.* **22**, 422-426.

de Kloet, E. R., Joëls, M. and Holsboer, F. (2005). Stress and the brain: from adaptation to disease. *Nat. Rev. Neurosci.* **6**, 463-475.

Egan, R. J., Bergner, C. L., Hart, P. C., Cachat, J. M., Canavello, P. R., Elegante, M. F., Elkhayat, S. I., Bartels, B. K., Tien, A. K., Tien, D. H. et al. (2009). Understanding behavioral and physiological phenotypes of stress and anxiety in zebrafish. *Behav. Brain Res.* **205**, 38-44.

Ferguson, G. A. (1981). *Statistical Analysis in Psychology and Education*, 5 edn. Singapore: McGraw Hill Book Company.

Fine, P. G. and Rosenfeld, M. J. (2013). The endocannabinoid system, cannabinoids, and pain. *Rambam Maimonides Med J* **4**, e0022.

Gerlai, R. (2010a). Zebrafish antipredatory responses: a future for translational research? *Behav. Brain Res.* **207**, 223-231.

Gerlai, R. (2010b). High-throughput behavioral screens: the first step towards finding genes involved in vertebrate brain function using zebrafish. *Molecules* **15**, 2609-2622.

Gorissen, M., Bernier, N. J., Manuel, R., de Gelder, S., Metz, J. R., Huising, M. O. and Flik, G. (2012). Recombinant human leptin attenuates stress axis activity in common carp (*Cyprinus carpio* L.). *Gen. Comp. Endocrinol.* **178**, 75-81.

Gorzalka, B. B., Hill, M. N. and Hillard, C. J. (2008). Regulation of endocannabinoid signaling by stress: implications for stress-related affective disorders. *Neurosci. Biobehav. Rev.* **32**, 1152-1160.

Guindon, J. and Hohmann, A. G. (2009). The endocannabinoid system and pain. *CNS Neurol. Disord. Drug Targets* **8**, 403-421.

Hill, M. N., McLaughlin, R. J., Pan, B., Fitzgerald, M. L., Roberts, C. J., Lee, T. T. Y., Karatsoreos, I. N., Mackie, K., Viau, V., Pickel, V. M. et al. (2011). Recruitment of prefrontal cortical endocannabinoid signaling by glucocorticoids contributes to termination of the stress response. *J. Neurosci.* **31**, 10506-10515.

Hurd, M. W., Debruyne, J., Straume, M. and Cahill, G. M. (1998). Circadian rhythms of locomotor activity in zebrafish. *Physiol. Behav.* **65**, 465-472.

Joëls, M., Karst, H., Krugers, H. J. and Lucassen, P. J. (2007). Chronic stress: implications for neuronal morphology, function and neurogenesis. *Front. Neuroendocrinol.* **28**, 72-96.

Kalueff, A. V., Gebhardt, M., Stewart, A. M., Cachat, J. M., Brimmer, M., Chawla, J. S., Craddock, C., Kyzar, E. J., Roth, A., Landsman, S. et al.; Zebrafish Neuroscience Research Consortium (2013). Towards a comprehensive catalog of zebrafish behavior 1.0 and beyond. *Zebrafish* **10**, 70-86.

Korte, S. M., Olivier, B. and Koolhaas, J. M. (2007). A new animal welfare concept based on allostasis. *Physiol. Behav.* **92**, 422-428.

Krugers, H. J., Lucassen, P. J., Karst, H. and Joëls, M. (2010). Chronic stress effects on hippocampal structure and synaptic function: relevance for depression and normalization by anti-glucocorticoid treatment. *Front Synaptic Neurosci* **2**, 24.

Lankford, S. E., Adams, T. E. and Cech, J. J., Jr (2003). Time of day and water temperature modify the physiological stress response in green sturgeon, Acipenser medirostris. *Comp. Biochem. Physiol.* **135A**, 291-302.

Lee, T. T. Y. and Hill, M. N. (2013). Age of stress exposure modulates the immediate and sustained effects of repeated stress on corticolimbic cannabinoid CB_1 receptor binding in male rats. *Neuroscience* **249**, 106-114.

Liu, I. Y. C., Lyons, W. E., Mamounas, L. A. and Thompson, R. F. (2004). Brain-derived neurotrophic factor plays a critical role in contextual fear conditioning. *J. Neurosci.* **24**, 7958-7963.

Löhr, H. and Hammerschmidt, M. (2011). Zebrafish in endocrine systems: recent advances and implications for human disease. *Annu. Rev. Physiol.* **73**, 183-211.

López-Olmeda, J. F., Blanco-Vives, B., Pujante, I. M., Wunderink, Y. S., Mancera, J. M. and Sánchez-Vázquez, F. J. (2013). Daily rhythms in the hypothalamus-pituitary-interrenal axis and acute stress responses in a teleost flatfish, *Solea senegalensis*. *Chronobiol. Int.* **30**, 530-539.

Lupien, S. J. and Lepage, M. (2001). Stress, memory, and the hippocampus: can't live with it, can't live without it. *Behav. Brain Res.* **127**, 137-158.

Lupien, S. J. and McEwen, B. S. (1997). The acute effects of corticosteroids on cognition: integration of animal and human model studies. *Brain Res. Brain Res. Rev.* **24**, 1-27.

Lynch, M. A. (2004). Long-term potentiation and memory. *Physiol. Rev.* **84**, 87-136.

Magariños, A. M. and McEwen, B. S. (1995). Stress-induced atrophy of apical dendrites of hippocampal CA3c neurons: involvement of glucocorticoid secretion and excitatory amino acid receptors. *Neuroscience* **69**, 89-98.

Mahabir, S., Chatterjee, D., Buske, C. and Gerlai, R. (2013). Maturation of shoaling in two zebrafish strains: a behavioral and neurochemical analysis. *Behav. Brain Res.* **247**, 1-8.
Mandillo, S., Tucci, V., Hölter, S. M., Meziane, H., Banchaabouchi, M. A., Kallnik, M., Lad, H. V., Nolan, P. M., Ouagazzal, A. M., Coghill, E. L. et al. (2008). Reliability, robustness, and reproducibility in mouse behavioral phenotyping: a cross-laboratory study. *Physiol. Genomics* **34**, 243-255.
Manuel, R., Gorissen, M., Roca, C. P., Zethof, J., van de Vis, H., Flik, G. and van den Bos, R. (2014). Inhibitory avoidance learning in zebrafish (*Danio rerio*): effects of shock intensity and unraveling differences in task performance. *Zebrafish* **11**, 341-352.
Maximino, C., Puty, B., Benzecry, R., Araújo, J., Lima, M. G., de Jesus Oliveira Batista, E., Renata de Matos Oliveira, K., Crespo-Lopez, M. E. and Herculano, A. M. (2013). Role of serotonin in zebrafish (*Danio rerio*) anxiety: relationship with serotonin levels and effect of buspirone, WAY 100635, SB 224289, fluoxetine and para-chlorophenylalanine (pCPA) in two behavioral models. *Neuropharmacology* **71**, 83-97.
McEwen, B. S. (2005). Glucocorticoids, depression, and mood disorders: structural remodeling in the brain. *Metabolism* **54 Suppl. 1**, 20-23.
McMillan, P. J., Wilkinson, C. W., Greenup, L., Raskind, M. A., Peskind, E. R. and Leverenz, J. B. (2004). Chronic cortisol exposure promotes the development of a GABAergic phenotype in the primate hippocampus. *J. Neurochem.* **91**, 843-851.
Morsink, M. C., Steenbergen, P. J., Vos, J. B., Karst, H., Joëls, M., de Kloet, E. R. and Datson, N. A. (2006). Acute activation of hippocampal glucocorticoid receptors results in different waves of gene expression throughout time. *J. Neuroendocrinol.* **18**, 239-252.
Mueller, T., Dong, Z., Berberoglu, M. A. and Guo, S. (2011). The dorsal pallium in zebrafish, *Danio rerio* (Cyprinidae, Teleostei). *Brain Res.* **1381**, 95-105.
Ng, M.-C., Hsu, C.-P., Wu, Y.-J., Wu, S.-Y., Yang, Y.-L. and Lu, K.-T. (2012). Effect of MK-801-induced impairment of inhibitory avoidance learning in zebrafish via inactivation of extracellular signal-regulated kinase (ERK) in telencephalon. *Fish Physiol. Biochem.* **38**, 1099-1106.
Norton, W. H. J. (2013). Toward developmental models of psychiatric disorders in zebrafish. *Front. Neural Circuits* **7**, 79.
Ögren, S. O., Eriksson, T. M., Elvander-Tottie, E., D'Addario, C., Ekström, J. C., Svenningsson, P., Meister, B., Kehr, J. and Stiedl, O. (2008). The role of 5-HT(1A) receptors in learning and memory. *Behav. Brain Res.* **195**, 54-77.
Olvera-Cortés, E., Cervantes, M. and González-Burgos, I. (2002). Place-learning, but not cue-learning training, modifies the hippocampal theta rhythm in rats. *Brain Res. Bull.* **58**, 261-270.
Pace, T. W. W. and Miller, A. H. (2009). Cytokines and glucocorticoid receptor signaling. Relevance to major depression. *Ann. New York Acad. Sci.* **1179**, 86-105.
Parker, M. O., Millington, M. E., Combe, F. J. and Brennan, C. H. (2012). Housing conditions differentially affect physiological and behavioural stress responses of zebrafish, as well as the response to anxiolytics. *PLoS ONE* **7**, e34992.
Pavlidis, M., Sundvik, M., Chen, Y.-C. and Panula, P. (2011). Adaptive changes in zebrafish brain in dominant-subordinate behavioral context. *Behav. Brain Res.* **225**, 529-537.
Pavlidis, M., Digka, N., Theodoridi, A., Campo, A., Barsakis, K., Skouradakis, G., Samaras, A. and Tsalafouta, A. (2013). Husbandry of zebrafish, *Danio rerio*, and the cortisol stress response. *Zebrafish* **10**, 524-531.
Piato, Â. L., Capiotti, K. M., Tamborski, A. R., Oses, J. P., Barcellos, L. J. G., Bogo, M. R., Lara, D. R., Vianna, M. R. and Bonan, C. D. (2011). Unpredictable chronic stress model in zebrafish (*Danio rerio*): behavioral and physiological responses. *Prog. Neuropsychopharmacol. Biol. Psychiatry* **35**, 561-567.
Radulovic, J., Rühmann, A., Liepold, T. and Spiess, J. (1999). Modulation of learning and anxiety by corticotropin-releasing factor (CRF) and stress: differential roles of CRF receptors 1 and 2. *J. Neurosci.* **19**, 5016-5025.
Reul, J. M. H. M. and de Kloet, E. R. (1985). Two receptor systems for corticosterone in rat brain: microdistribution and differential occupation. *Endocrinology* **117**, 2505-2511.
Roozendaal, B., McEwen, B. S. and Chattarji, S. (2009). Stress, memory and the amygdala. *Nat. Rev. Neurosci.* **10**, 423-433.
Schaaf, M. J. M., Chatzopoulou, A. and Spaink, H. P. (2009). The zebrafish as a model system for glucocorticoid receptor research. *Comp. Biochem. Physiol.* **153A**, 75-82.
Schoonheim, P. J., Chatzopoulou, A. and Schaaf, M. J. M. (2010). The zebrafish as an in vivo model system for glucocorticoid resistance. *Steroids* **75**, 918-925.
Silverman, M. N. and Sternberg, E. M. (2012). Glucocorticoid regulation of inflammation and its functional correlates: from HPA axis to glucocorticoid receptor dysfunction. *Ann. N. Y. Acad. Sci.* **1261**, 55-63.
Singh, A., Subhashini, N., Sharma, S. and Mallick, B. N. (2013). Involvement of the α1-adrenoceptor in sleep-waking and sleep loss-induced anxiety behavior in zebrafish. *Neuroscience* **245**, 136-147.
Sison, M. and Gerlai, R. (2010). Associative learning in zebrafish (*Danio rerio*) in the plus maze. *Behav. Brain Res.* **207**, 99-104.
Stephenson, J. F., Whitlock, K. E. and Partridge, J. C. (2011). Zebrafish preference for light or dark is dependent on ambient light levels and olfactory stimulation. *Zebrafish* **8**, 17-22.
Stewart, A. M., Braubach, O., Spitsbergen, J., Gerlai, R. and Kalueff, A. V. (2014). Zebrafish models for translational neuroscience research: from tank to bedside. *Trends Neurosci.* **37**, 264-278.
Stolte, E. H., Nabuurs, S. B., Bury, N. R., Sturm, A., Flik, G., Savelkoul, H. F. J. and Lidy Verburg-van Kemenade, B. M. (2008). Stress and innate immunity in carp: corticosteroid receptors and pro-inflammatory cytokines. *Mol. Immunol.* **46**, 70-79.
Suri, D. and Vaidya, V. A. (2013). Glucocorticoid regulation of brain-derived neurotrophic factor: relevance to hippocampal structural and functional plasticity. *Neuroscience* **239**, 196-213.
ter Horst, J. P., van der Mark, M. H., Arp, M., Berger, S., de Kloet, E. R., Oitzl, M. S. (2012). Stress or no stress: mineralocorticoid receptors in the forebrain regulate behavioral adaptation. *Neurobiol. Learn. Mem.* **98**, 33-40.
Upadhya, M. A., Nakhate, K. T., Kokare, D. M., Singru, P. S. and Subhedar, N. K. (2011). Cocaine- and amphetamine-regulated transcript peptide increases spatial learning and memory in rats. *Life Sci.* **88**, 322-334.
Upadhya, M. A., Kokare, D. M. and Subhedar, N. K. (2013). Cocaine- and amphetamine-regulated transcript peptide (CART) in the central nucleus of amygdala potentiates behavioral and hormonal responses of the rat exposed to its predator. *Behav. Brain Res.* **243**, 129-137.
Vandesompele, J., De Preter, K., Pattyn, F., Poppe, B., Van Roy, N., De Paepe, A. and Speleman, F. (2002). Accurate normalization of real-time quantitative RT-PCR data by geometric averaging of multiple internal control genes. *Genome Biol.* **3**, research0034.1.
Vignet, C., Bégout, M.-L., Péan, S., Lyphout, L., Leguay, D. and Cousin, X. (2013). Systematic screening of behavioral responses in two zebrafish strains. *Zebrafish* **10**, 365-375.
Wahlsten, D., Bachmanov, A., Finn, D. A. and Crabbe, J. C. (2006). Stability of inbred mouse strain differences in behavior and brain size between laboratories and across decades. *Proc. Natl. Acad. Sci. USA* **103**, 16364-16369.
Webster, J. C., Oakley, R. H., Jewell, C. M. and Cidlowski, J. A. (2001). Proinflammatory cytokines regulate human glucocorticoid receptor gene expression and lead to the accumulation of the dominant negative beta isoform: a mechanism for the generation of glucocorticoid resistance. *Proc. Natl. Acad. Sci. USA* **98**, 6865-6870.
Williams, F. E., White, D. and Messer, W. S. (2002). A simple spatial alternation task for assessing memory function in zebrafish. *Behav. Processes* **58**, 125-132.
Wilson, R. I. and Nicoll, R. A. (2002). Endocannabinoid signaling in the brain. *Science* **296**, 678-682.
Wiltgen, B. J., Sanders, M. J., Anagnostaras, S. G., Sage, J. R. and Fanselow, M. S. (2006). Context fear learning in the absence of the hippocampus. *J. Neurosci.* **26**, 5484-5491.
Xu, X., Scott-Scheiern, T., Kempker, L. and Simons, K. (2007). Active avoidance conditioning in zebrafish (*Danio rerio*). *Neurobiol. Learn. Mem.* **87**, 72-77.
Yan, W., Zhang, T., Jia, W., Sun, X. and Liu, X. (2011). Chronic stress impairs learning and hippocampal cell proliferation in senescence-accelerated prone mice. *Neurosci. Lett.* **490**, 85-89.
Yermolaieva, O., Chen, J., Couceyro, P. R. and Hoshi, T. (2001). Cocaine- and amphetamine-regulated transcript peptide modulation of voltage-gated Ca^{2+} signaling in hippocampal neurons. *J. Neurosci.* **21**, 7474-7480.
Zhou, J. and Cidlowski, J. A. (2005). The human glucocorticoid receptor: one gene, multiple proteins and diverse responses. *Steroids* **70**, 407-417.
Zhou, M., Bakker, E. H. M., Velzing, E. H., Berger, S., Oitzl, M., Joëls, M. and Krugers, H. J. (2010). Both mineralocorticoid and glucocorticoid receptors regulate emotional memory in mice. *Neurobiol. Learn. Mem.* **94**, 530-537.