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Understanding how stress responses and stress-related behaviors have evolved in zebrafish and mammals

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ABSTRACT

Stress response is essential for the organism to quickly restore physiological homeostasis disturbed by various environmental insults. In addition to well-established physiological cascades, stress also evokes various brain and behavioral responses. Aquatic animal models, including the zebrafish (*Danio rerio*), have been extensively used to probe pathobiological mechanisms of stress and stress-related brain disorders. Here, we critically discuss the use of zebrafish models for studying mechanisms of stress and modeling its disorders experimentally, with a particular cross-taxon focus on the potential evolution of stress responses from zebrafish to rodents and humans, as well as its translational implications.

1. Introduction

Stress response is a complex set of physiological reactions that aim to restore body homeostasis disturbed by various environmental insults by activating the sympatho-adrenomedullary system (SAM) and the hypothalamic-pituitary-adrenal axis (HPA) (Russell and Lightman, 2019; Wendelaar Bonga, 1997b). Stress affects human and animal central nervous system (CNS) via multiple mechanisms (Carlson and Rosser-Hogan, 1991; Johansson et al., 2010; Lee et al., 2015; Resnick et al., 2003), including dysregulated neurotransmitters, hormones and expression of key brain genes (Conrad, 2008; McGonigle, 2014; Russell and Lightman, 2019). While normal stress responses are fundamental for organismal survival, pathological stress can be detrimental, causing various brain illnesses, such as anxiety, depression and post-traumatic stress disorder (PTSD) (Cohen et al., 2007; Cohen and Williamson, 1991; McEwen and Stellar, 1993).

Animal models, especially rodents, have been extensively used to study neural mechanisms of stress and stress-related neuropathology (Campos et al., 2013; de Abreu et al., 2021; Patchev and Patchev, 2006; Spagnoli et al., 2016). In addition to mammals, the zebrafish (*Danio rerio*) and other fishes have demonstrated high relevance to modeling stress responses in vivo (Demin et al., 2020; Spagnoli et al., 2016), as they possess an evolutionarily conserved hypothalamic-pituitary-interrenal (HPI) stress axis that is structurally and functionally homologous to the mammalian HPA axis (Alsop and Vijayan, 2008, 2009). Fishes also have a generally similar brain architectonics (Wullimann et al., 1996) (Fig. 1),

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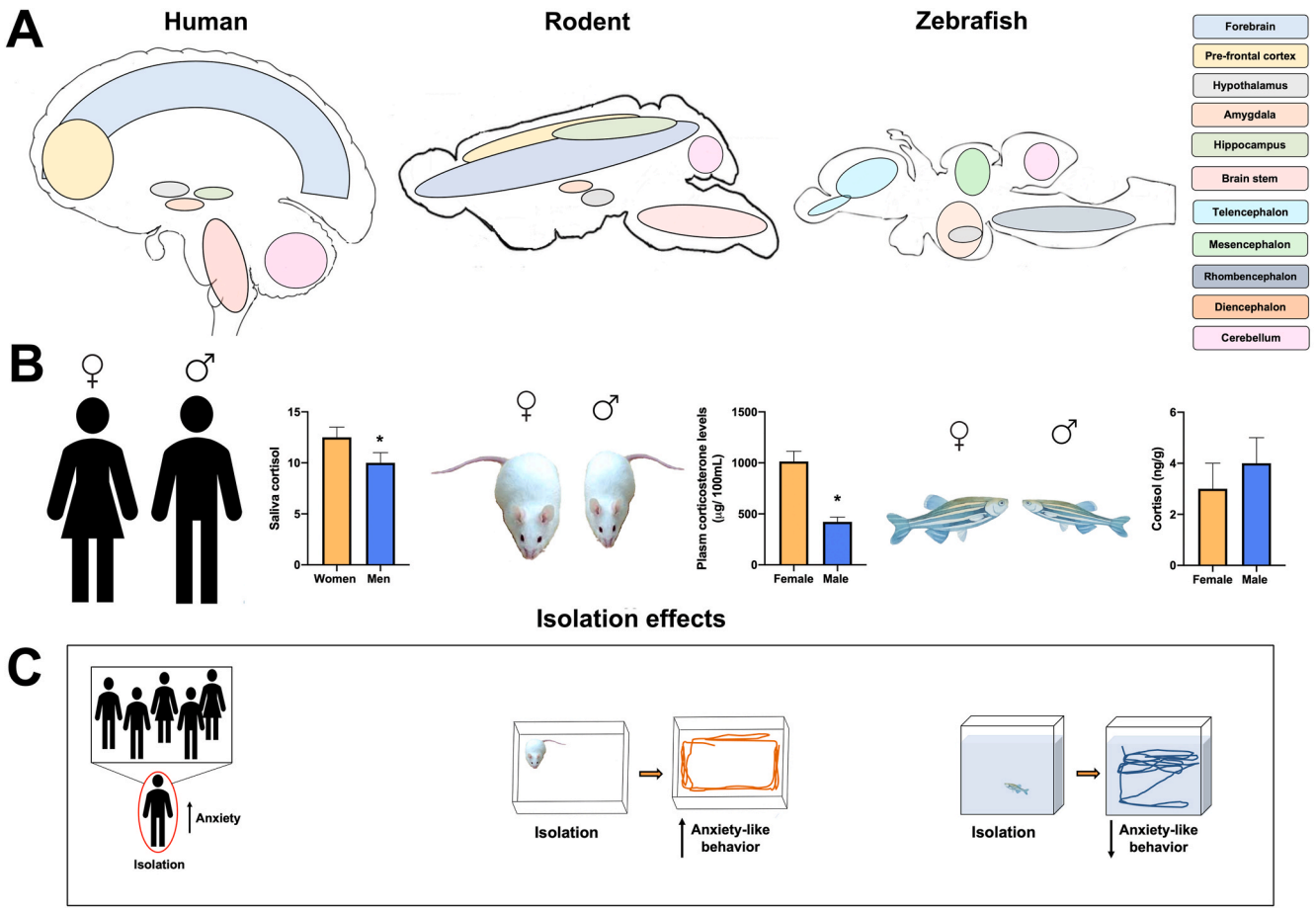

Fig. 1. Selected examples of similarities and differences between fish and mammalian stress responses. Panel (A) summarizes brain areas involved in stress response in zebrafish, rodents and mammals (also see Table 3). Panel (B) illustrates sex differences in baseline stress glucocorticoid levels in humans, rodents and zebrafish (female mammals > males (Larsson et al., 2009), zebrafish males = females (Wong et al., 2019)). Panel (C) shows distinct effects of chronic social isolation across these species, increasing the risk of mental disorders (e.g., anxiety) in mammals (Lukkes et al., 2009; Santini et al., 2020), but seemingly reducing anxiety-like behavior in zebrafish (Parker et al., 2012; Shams et al., 2015).

with multiple shared neurotransmitters and hormones involved in stress responses, between the two taxa (Panula et al., 2010). Here, we evaluate the developing utility of zebrafish models for studying mechanisms of stress and stress-related disorders, with a particular focus on the evolution and translational relevance of stress responses in fish and rodents.

2. Physical and psychological stress responses in fishes, rodents and humans

Stress responses in vivo generally vary based on the type of stressors (physical or psychological) applied. In mammals, psychological stress (e.g., aversive environmental stimuli or predator-related cues) and physical stress (e.g., hemorrhage or infection) engage distinct neural and cellular networks in the brain (Dayas et al., 2001; Godoy et al., 2018). For instance, physical stressors are mainly processed by mammalian brainstem and hypothalamic regions (Dayas et al., 2001; De Kloet et al., 2005; Fenoglio et al., 2006; Ulrich-Lai and Herman, 2009), where the SAM system provides rapid behavioral adaptations, such as alertness, vigilance and appraisal of the situation (De Kloet et al., 2005; Joëls and Baram, 2009). The HPA axis becomes activated later through the brainstem, with the paraventricular nucleus (PVN) of the hypothalamus activating or inhibiting this axis (Ulrich-Lai and Herman, 2009). Physical stressors also activate other brain structures that regulate autonomic stress responses, including nucleus of the solitary tract (NTS) and dorsomedial hypothalamus (DMH) (Geerling et al., 2010). The key brain regions involved in physical stressors also include the amygdala, the hippocampus and the prefrontal cortex (PFC) that receive inputs from cortical and subcortical areas, whose outputs converge to subcortical relay sites, hence enabling downstream processing of limbic information (Ulrich-Lai and Herman, 2009).

Psychological stressors can elicit strong physiological, behavioral and cognitive responses in humans (Skoluda et al., 2015) and rodents (Finnell et al., 2017; Pryce and Fuchs, 2017). Together with the prosencephalic nuclei, limbic circuits (the amygdala, the hippocampus, PVN, the ventral tegmental area and the nucleus accumbens) modulate psychological stress in mammals (Russo and Nestler, 2013; Ulrich-Lai and Herman, 2009). The PFC is also important for stress responses (Ridderinkhof et al., 2004), as bilateral lesions of the prelimbic cortex (PLC) in rodents increase plasma level of the adrenocorticotrophic hormone (ACTH), corticosterone and the PVN expression of Fos protein (Diorio et al., 1993; Figueiredo et al., 2003b). In contrast, lesioning the infralimbic cortex (ILC) reduces corticosterone secretion, suggesting that PLC and ILC may play opposite roles in responses to psychological stressors (Sullivan and Gratton, 1999). Mammalian PFC also projects to the amygdala, forming a corticolimbic circuit critical for processing both emotional (Gabbott et al., 2005; LeDoux, 2007) and physical (e.g., restraint) stress (Cullinan et al., 1995; Janak and Tye, 2015).

Glucocorticoids, including human or fish cortisol and rodent corticosterone, are biosynthesized and released during stress, to reach their target organs (Joëls et al., 2018; Sadoul and Geffroy, 2019). The biological effects of these stress hormones are mediated by mineralocorticoid (MR) and glucocorticoid (GR) receptors (Katsu and Iguchi, 2016;

Table 1
Selected examples of effects of acute stress response on fish cortisol levels.

Acute stress response	Species	Increased cortisol levels	References
Alarm substance of conspecifics (15 min)	Zebrafish (*Danio rerio)*	Whole-body	Abreu et al. (2017)
Social isolation for 15 min	Zebrafish	Whole-body	Kalueff et al. (2014a)
Net chasing (2 min)	Zebrafish	Whole-body	de Abreu et al. (2014)
Net chasing (for 1 min)	Jundiá (*Rhamdia quelen*), nile tilapia (*Oreochromis niloticus)*	Plasma	(Barcellos et al., 1999; Cericato et al., 2008)
Physical restraint (15 min)	Zebrafish	Whole-body	Abreu et al. (2017)
Air exposure (1 min)	Zebrafish	Whole-body	Abreu et al. (2015)
Repeated electric shock (20 V, 15 mA, 100 Hz for 1 min every 4 min, for 60 min)	Nile tilapia	Plasma	Barreto and Volpato (2006)
Acute handling and restraint	Atlantic salmon (*Salmo salar*)	Plasma	Carey and McCormick (1998)
Cold shock (28–18 °C)	Matrinxã (*Brycon amazonicus*)	Plasma	Inoue et al. (2008)
Aerial emersion handling stressor	Pallid (*Scaphirhynchus albus*) and hybrid pallidxshovelnose (*S. albusxplatorynchus*) sturgeons	Plasma	Barton et al. (2000)
Handling (30-s air exposure)	Lake (*Salvelinus namaycush),* rainbow (*Oncorhynchus mykiss),* brown (*Salmo trutta)* and brook trouts (*Salvelinus fontinalis)*	Plasma	Barton (2000)
Transportation for 2h	Lake, rainbow, brown and brook trouts	Plasma	Barton (2000)

McEwen et al., 2015; Pippal et al., 2011; Schaaf et al., 2008) that are co-expressed particularly abundantly in the limbic neurons (De Kloet et al., 2005; Herman et al., 2003; Joëls et al., 2012). Glucocorticoids are also responsible for biofeedback inhibition of ACTH secretion from the pituitary and corticotropin-releasing hormone (CRH) secretion from the hypothalamus (De Kloet et al., 2005; Russell and Lightman, 2019). As MRs are implicated in the appraisal and the onset of stress response, GRs (with a ~10-fold lower affinity for corticosteroids) are activated by high levels of these hormones (Reul and Kloet, 1985) and directly affect synaptic transmission, plasticity, learning, and memory (Finsterwald and Alberini, 2014), in addition to modulating multiple other (e.g., metabolic and immune) physiological systems (De Kloet et al., 2005).

Like other vertebrates, various fish species display robust physiological and behavioral stress responses (Schreck and Tort, 2016; Wendelaar Bonga, 1997b), with similar neurochemical and neuroendocrine mechanisms to those in mammals (Table 1). A small freshwater teleost fish, the zebrafish has rapidly become a powerful novel model system in stress neuroscience research (de Abreu et al., 2021; Demin et al., 2020; Kalueff et al., 2014b; Stewart et al., 2014). Similar to mammals, fish also display distinct, type-specific stress responses (Demin et al., 2020; Khan et al., 2017). For example, physical stressors like acute net chasing cause stronger cortisol release in zebrafish than do psychological stressors, such as the alarm substance or conspecific blood exposure (Abreu et al., 2017). While zebrafish acutely subjected to a mild stressor (e.g., 1-min air exposure) show unaltered brain gene expression for interleukins (IL) IL-1β and IL-6, brain-derived neurotrophic factor (BDNF), interferon gamma (IFN-γ) and tumor necrosis factor-alpha (TNF-α) (Kirsten et al., 2020), a more severe acute stress (e.g., a 90-min exposure to cold water, bright light, vortex, shallow water and restraint) upregulates brain mRNA expression of all these genes (Yang et al., 2020). Taken together, these findings demonstrate that stress responses in both fish and mammals are physiologically similar (and, hence, seemingly evolutionarily conserved), especially since they are both directly (and in a similar manner) influenced by the type, intensity, frequency and duration of stress.

Similar to mammalian HPA axis, stress also activates the fish HPI axis to trigger the hypothalamus (especially nucleus preopticus, NPO, homologous to the mammalian PVN) to initiate CRH/ACTH cascade-stimulated synthesis and release of cortisol by the interrenal tissue (Sumpter et al., 1994; Wendelaar Bonga, 1997b). Released by NPO, CRH also stimulates the secretion of proopiomelanocortin (POMC) in the fish anterior pituitary, reaching it via direct projections from NPO (LederiS et al., 1994). POMC is an evolutionary conserved polypeptide expressed in fishes (Arends et al., 1998; Gonzalez-Nunez et al., 2003), rodents and humans (Chang et al., 1980), that acts as a precursor for ACTH, as well as α- and β-melanocyte-stimulating hormone (MSH). Like in mammals, fish ACTH is the primary hormone responsible for stimulating cortisol secretion (Wendelaar Bonga, 1997a) and controlling its biosynthesis via the melanocortin receptor 2 (MC2R) (Roebuck et al., 1984; Schioth et al., 1996). Produced cortisol is next released into the circulation where its effects on fish target organs, like in mammals, are modulated by MRs and GRs (Pippal et al., 2011; Schaaf et al., 2008).

In addition to glucocorticoids, stress also triggers catecholamine release from fish chromaffin cells, with a rapid rise in blood glucose (Barton and Iwama, 1991; Randall and Ferry, 1992; Wendelaar Bonga, 1997b), as well as epinephrine and norepinephrine (Eto et al., 2014; Nikinmaa, 1992). Stressors can also indirectly modulate brain neurotransmitters (Wendelaar Bonga, 1997b), such as serotonin and dopamine and its metabolites, since zebrafish acutely isolated for 24 h exhibit increase serotonin and reduce its metabolite 5-hydroxyindoleacetic acid (5HIAA) levels, as well as dopamine and its metabolite 3,4-dihydroxyphenylacetic acid (DOPAC) (Shams et al., 2017). In addition to altered monoaminergic system, fish chromaffin cells also respond less to cholinergic stimulation following a prolonged physical stress (Reid and Perry, 1994). As fish share a high genetic homology of stress-related genes with their human and rodent analogs (i.e., estimated as 62–64% genetic sequence homology in zebrafish vs. humans and mice, Table 2), several other shared aspects of stress responses will be analyzed further, and compared across the three species.

In addition to physiological and genetic similarities discussed above, some interesting differences in neurobiology of zebrafish vs. mammalian stress responses also exist. For example, exposure of zebrafish to chronic stress increases brain BDNF levels (Song et al., 2018), which are usually reduced (in most, but not all, brain areas) by chronic stress in rodents and humans (Karege et al., 2002; Licinio and Wong, 2002; Radahmadi et al., 2015), as well as in patients with affective disorders, such as PTSD, anxiety and depression (Bremner et al., 2000; Chen et al., 2006; Duman and Monteggia, 2006; Mervaala et al., 2000). In contrast, the overexpression of brain BDNF evokes anxiolytic and antidepressant effects in rodents (Deltheil et al., 2009; Gourley et al., 2008), with a similar therapeutic effect observed following a BDNF augmentation clinically (Brunoni et al., 2008; Zhou et al., 2017). The latter difference may result from a generally higher neuroprotective potential of fish (vs. potentially more 'fragile' mammalian) CNS, which may also play a role during stress. Another physiological difference concerns corticosteroid hormones utilized by rodents, humans and fish for their stress responses: while humans and zebrafish utilize cortisol (and laboratory rodents do show some cortisol activity as well) (Bhat et al., 2007; Gong et al., 2015; Hawley and Keevil, 2016; Kulle et al., 2013), the major stress corticosteroid in reptiles, birds and laboratory rodents is corticosterone (Nussey and Whitehead, 2001; Raff et al., 2011; Sadoul and Geffroy, 2019; Usa et al., 2007). In zebrafish and humans, cortisol is produced in the adrenal gland during stress by 17-a hydroxylase, CYP17 (Wang and Ge, 2004), an enzyme lacking in rodents (Gallo-Payet and Battista, 2011). As

Table 2
Major zebrafish genes related to stress response and their human and mouse orthologues, based on the National Center for Biotechnology Information (NCBI) Genetic Testing Registry (GTR) database with % homology calculated based on protein identity using the HomoloGene database (www.ncbi.nlm.nih.gov/homologene/).

Zebrafish genes	Symbol	Mouse genes	Human genes	% Homology		
				Zebra-fish *vs* Human	Zebra-fish *vs* Mouse	Human *vs* Mouse
Proopiomelanocortin a	*pomca*	*POMC*	*Pomc*	41	43	71
Melanocortin 2 receptor	*mc2r*	*Mc2r*	*MC2R*	50	51	89
Melanocortin 1 receptor	*mc1r*	*Mc1r*	*MC1R*	58	58	76
Corticotropin releasing hormone b	*crhb*	*Crh*	*CRH*	92	42	83
Corticotropin releasing hormone binding protein	*crhbp*	*Crhbp*	*CRHPB*	63	61	87
Fos proto-oncogene	*fos*	*Fos*	*FOS*	61	62	93
Jun proto-oncogene	*jun*	*Jun*	*JUN*	78	79	97
Brain derived neurotrophic factor	*bdnf*	*Bdnf*	*BDNF*	80	79	97
Early growth response protein 1	*egr1*	*Egr1*	*EGR1*	66	63	91
Glucocorticoid receptor	*nr3c1*	*Nr3c1*	*NR3C1*	54	55	90
Mineralocorticoid receptor	*nr3c2*	*Nr3c2*	*NR2C2*	54	53	90
	nr3c2vit			41	39	
Serotonin transporter	slc6a4	*Slc6a4*	*SLC6A4*	70	70	92
GABA (A) α6 receptor subunit	gabra6	*Gabra6*	*GABRA6*	76	76	92
Opioid receptor μ1	oprm1	*Oprm1*	*OPRM1*	78	81	94
Tryptophan hydroxilase 1	Tph1a	*Tph1*	*TPH1*	80	78	90
	Tph1b			77	75	
Tryptophan hydroxilase 2	tph2	*Tph2*	*TPH2*	76	79	93
P2x ligand-gated ion channel 7	p2rx7	*P2rx7*	*P2RX7*	46	46	80
Alpha-1 A adrenergic receptor	*adra1a*	*Adra1a*	*ADRA1A*	62	61	91
Alpha-1 B adrenergic receptor	*adra1ba*	*Adra1b*	*ADRA1B*	68	67	96
	adra1bb			70	70	
Alpha-2 A adrenergic receptor	*adra2a*	*Adra2a*	*ADRA2A*	67	68	92
Alpha-2 B adrenergic receptor	*adra2b*	*Adra2b*	*ADRA2B*	57	65	83
	adra2b-like			56	55	
Alpha-2 C adrenergic receptor	*adra2c*	*Adra2c*	*ADRA2C*	68	65	89
Alpha-2 D adrenergic receptor	*adra2d*	[a]	[a]	[b]		
Beta-1 adrenergic receptor	*adrb1*	*Adrb1*	*ADRB1*	64	63	90
Beta-2 adrenergic receptor	*adrb2a*	*Adrb2*	*ADRB2*	58	56	87
	adrb2b			60	62	
Beta-3 adrenergic receptor	*adrb3a*	*Adrb3*	*ADRB3*	57	58	81
Average % homology				**64**	**62**	**88**

[a] Absent in fish.
[b] Absent in mammals.

such, some species differences in stress neuroendocrinology may play a role in how fish and rodents respond to acute and chronic stressors.

Certain anatomical differences in brain morphology, especially within the limbic system of mammals and fishes (Fig. 1), may also contribute to some variance in physiological and behavioral responses to stress across these species (Herman et al., 2005; Price, 2013). For instance, acute restrain stress, a common stress protocol used to induces stress-related behaviors, differentially affects animal limbic system (Herman et al., 2005), in rats increasing, and in zebrafish decreasing, paraventricular nucleus CRH mRNA expression (Ghisleni et al., 2012; Liu et al., 2011). Likewise, lesions of rodent anterior cingulate and medial prefrontal cortex, lacking in zebrafish (Parker et al., 2013), enhance ACTH and corticosterone secretion following restraint stress (Diorio et al., 1993; Figueiredo et al., 2003a), which is impossible in zebrafish given the lack of prefrontal cortex. Together, this suggests that neuromorphological differences between fishes and mammals may contribute to some distinct physiological and behavioral responses to stress between zebrafish and mammals. Moreover, some physiological and behavioral responses to stress also differ between fish and mammals in models based on early maternal separation (Andersen et al., 1999). For example, while in rodents the latter stress increases anxiety-like behavior, hypothalamic CRF mRNA levels and corticosterone levels when adults (Bondar et al., 2018; Plotsky and Meaney, 1993; Vargas et al., 2016), early social deprivation does not seem to affect baseline whole-body cortisol levels in adult zebrafish (Shams et al., 2020). Furthermore, zebrafish maternal stress (maternal starvation for 4 days) decreases cell proliferation in larval offspring forebrain at 5 days post-fertilization (dpf), whereas 10-hpf embryos born from a starved mother show elevated cortisol levels, indicating that maternal starvation stress does induce neurodevelopmental changes in zebrafish (Higuchi, 2020). Notable physiological differences have also been demonstrated in animal models of physical vs. psychical stressors. For example, adult male rats exhibit GR-mediated hippocampal atrophy and behavioral abnormalities on the second week of physical (electric footshock) stress, but not until the fourth week of psychological stress (e.g., witnessing conspecifics experiencing electric foot shock) (Li et al., 2019). In rodents, behavioral (e.g., thigmotaxis in the open field test) and molecular (e.g., decreased hippocampal GR expression) effects of such physical stressors appear early, but are relatively moderate, compared to the later-onset, but more pronounced impact of psychological stressors (Li et al., 2019). In zebrafish, while acute exposure to both physical (Ramsay et al., 2009) and chemical (Abreu et al., 2017) stressors increases whole-body cortisol levels and evokes anxiety-like behavior, putative physiological differences between physical vs. psychological stressors remain poorly understood. As these two types of stressors may activate different brain areas and distinct pools of GR/MR receptors, this may cause potentially distinct behavioral and physiological responses depending on the type of stressor.

In mammals, behavioral responses to acute stressor, often described as a 3-F (fight, freeze or flee) triad, are medicated by stress circuits, including the limbic-HPA regions comprised of cortex, hippocampus, nucleus accumbens, lateral septum, several hypothalamic nuclei, medial and cortical amygdaloid nuclei, dorsal raphe, locus coeruleus and brainstem nuclei (Brunoni et al., 2008; Ressler, 2010). It has recently been suggested that rodent stress response may also elicit characteristic self-grooming behavior as part of the 'fight, freeze, flight or groom' behavioral tetrad (Song et al., 2016b). While the prominent role of rodent self-grooming behavior and its patterning under stress is being widely recognized (Kalueff et al., 2016b; Song et al., 2016a), and likely represents an evolutionarily conserved trait in multiple species, fishes

seem to lack clear-cut grooming analogous behavior, and its role in fish behavior remains unclear, thus meriting further scrutiny. Likewise, facial expression phenotypes have recently been linked to rodent social activity, aggression (Brecht and Freiwald, 2012), pain (Langford et al., 2010; Sperry et al., 2018) and well-being status and stress (Andresen et al., 2020), thus, making facial expression potentially useful and sensitive biomarker of stress in mammals (also see similar important role of human facial expression in stress (Mayo and Heilig, 2019). However, while mammals have a remarkably complex facial muscles (Brecht and Freiwald, 2012; Burrows et al., 2006), little is known about facial responses to stress in fishes, clearly meriting further translational studies.

3. Effects of social environment and age on stress in zebrafish and mammals

Social environment is a complex factor modulating rodent (Beery and Kaufer, 2015), human (Santini et al., 2020) and zebrafish behavior (Fontana et al., 2021). As already mentioned, social deficits, such as early deprivation, isolation, hierarchy, crowding and social instability, cause experimental stress in rodents and zebrafish (Beery and Kaufer, 2015; Demin et al., 2020). For example, over-crowded zebrafish (40 fish/L) exhibit higher whole-body cortisol than fish maintained at a low (0.25-fish/L) density (Ramsay et al., 2006). In rodents, crowding activates the HPA axis and causes social avoidance (Lee et al., 2018), adrenal hypertrophy (Christian, 1971) and elevated corticosterone (Brown and Grunberg, 1995). In zebrafish, social stress can also be modeled by social isolation, since zebrafish, individually housed for 2 weeks, spend less time in the bottom of the novel tank (an anxiolytic-like effect) (Parker et al., 2012) and more time in the center of the open-tank (an anxiolytic-like effect) (Shams et al., 2015). These socially isolated fish also display lower baseline cortisol levels (Parker et al., 2012) and blunted cortisol responses to an acute stressor (e.g., 2-min net chasing), than group-housed fish (Giacomini et al., 2015). While a short-term 15-min social isolation evokes robust anxiety-like behavioral and cortisol responses in adult zebrafish (Kalueff et al., 2014a), rodent social isolation evokes hyperadrenocorticism, reduced body weight, altered blood composition and enhanced pain responsivity (in females) (Hatch et al., 1965; Valzelli, 1973), as well as anxiety/fear-like behaviors and poor social interaction (in males) (Lukkes et al., 2009). Overall, these findings demonstrate generally similar effects of social factors on the development of stress responses in zebrafish and mammals.

However, there are also some interesting distinct effects of chronic social isolation stress between zebrafish, rodents and humans (Fig. 1), since in mammals it increases the risk of mental disorders (e.g., anxiety) (Lukkes et al., 2009; Santini et al., 2020), but causes an anxiolytic-like effect in zebrafish (Parker et al., 2012; Shams et al., 2015) (Fig. 1). On the one hand, these differences may be due to potentially faster adaptation to novel environment (e.g., to isolation) and brain modulation (e.g., altered neurogenesis) in fish compared to mammals (Grandel et al., 2006; Kaslin et al., 2008). Another potential contributing factor can be some genetic differences, mostly due to teleost-specific genome duplication in zebrafish (Howe et al., 2013). For example, while mammals have two parathyroid hormone (PTH) receptor genes (*PTH1R* and *PTH2R)* vs. three in zebrafish (*pth1r*, *pth2r* and *pth3r)* (Gensure et al., 2004; Hogan et al., 2005), already associated with social isolation effects (e.g., down-regulating *pth2* gene in zebrafish (Anneser et al., 2020)).

Age also plays an important role in modulating stress responses (Novais et al., 2017). In both men and women, evening cortisol is higher in older than younger subjects (Gutchess et al., 2019; Larsson et al., 2009), and the HPA axis responsiveness varies during puberty, as 15-year-old individuals display higher cortisol levels in response to social stress test than 9-11-year-olds (Gunnar et al., 2009). In rodents, behavioral impact of stress also differs between ages (Novais et al., 2017), as adolescent female rats avoid a resident female, whereas adult females are more active and aggressive (Ver Hoeve et al., 2013). Adolescent female (but not male) rats exhibit less anxiety following social defeat stress, but equally high adult anxiety in both sexes (McCormick et al., 2008). Paralleling mammalian age-specific data, acute stress (e.g., 30-s air exposure) unalters anxiety-like behavior and whole-body cortisol in young (Aponte and Petrunich-Rutherford, 2019), but not adult zebrafish (Tran et al., 2014; Tran and Gerlai, 2015). Age also influences zebrafish locomotor activity, as aging 18-month old zebrafish are more immobile than young (6–9-months old) fish in the novel tank test (Evans et al., 2021). Collectively, this suggests that age gradually, and generally in a rather similar manner, impacts zebrafish, rodents and human stress responses.

Interestingly, some age aspects of the three model species may also factor into differential shaping of their stress responses. For example, humans become adults at the age of 20, old at 65, and live ~80 years (Wilson et al., 2019). Laboratory mice are considered adults at 2 months, old at 1.5–2 years, and have a lifespan of 2.5–3 years (Flurkey and Harrison, 2007), whereas laboratory zebrafish become young adults at the age of 3 months, old at 30 months, and live ~4 years (Kishi et al., 2009). As such, humans have a shorter adulthood (75% of the respective lifespan), compared 83% in mice and especially 94% in zebrafish. The duration of 'mature' adulthood (from adult to old) also varies, ranging from ~56% in humans and mice to 63% in zebrafish. Likewise, humans seem to have relatively shorter old age (20%), compared to mice (33%) and zebrafish (38%). The latter aspects, in turn, may underlie potential species differences in stress responses. For example, this may hypothetically render humans more vulnerable to stress (than mice and zebrafish) by being relatively more exposed to early-life stressors. At the same time, such age structure differences may also provide the three species with distinct *temporal* opportunities for coping, e.g., making zebrafish relatively more stress-resistant by 'extending' the life period when their brain is *mature* and can therefore most efficiently cope with stress, compared to mammals. Clearly, these features merit further scrutiny and further cross-species analyses.

4. Sex differences in stress responses in zebrafish, rodents and humans

Sex differences are increasingly reported in response of acute or chronic stressors exposure in zebrafish, rodents and humans. For example, unpredictable chronic stress lowers aggression and whole-body cortisol in female zebrafish (Rambo et al., 2017), but shows no differences in baseline cortisol levels between the sexes (Wong et al., 2019). In salmonids, plasma cortisol is higher in females vs. males (Idler and Freeman, 1968), whereas female rodents show higher baseline corticosterone (Bangasser and Wicks, 2017; Handa et al., 1994; Kitay, 1961) and corticosterone responses to stress (Bangasser and Valentino, 2014; Seale et al., 2004) than males. This also parallels clinical data on higher baseline cortisol in women (Larsson et al., 2009), who are also more likely to develop serious stress-related disorders, including anxiety, depression and PTSD (Hu et al., 2017; McLean et al., 2011; Patten et al., 2006).

While crowding stress particularly strongly affects male mammals, it is either calming or inactive in females (Brown and Grunberg, 1995; Kotrschal et al., 2007). In rodents, even when the same event is stressful to both males and females, the sequelae of stress exposure may differ, for example, impairing classical conditioning in females, but improving in males (Wood and Shors, 1998). The most prominent model of rodent social stress is the social defeat, typically induced in a resident-intruder test where a test subject is paired with a dominant resident (Martinez et al., 1998). Some sex differences have also been observed in this rodent model (Steinman and Trainor, 2017), as both sexes show similar rates of freezing when confronted with an aggressive resident, yet females make more attempts to flee (Trainor et al., 2013). As zebrafish dominance is associated with a greater body size and aggression, dominant males are generally more aggressive than dominant females (Paull et al., 2010). While male zebrafish over-express whole-brain *crf* (Evans et al., 2021), adult females display higher locomotion after repeated daily stress

(Devaud et al., 2019). Thus, some sex differences in stress-related behaviors (e.g. (Fontana et al., 2019; Genario et al., 2020; Maeng and Milad, 2015; McHenry et al., 2014),) appear to be conserved across these species, thereby raising the possibility of their shared or overlapping natural evolution.

5. Individual and strain differences in zebrafish, rodent and humans stress responses

Individual differences strongly impact biological and behavioral stress responses, forming resilient and vulnerable groups (Heinzelmann and Gill, 2013). Vulnerable subjects poorly adjust to stressors and express inappropriate responses, while resilient subjects distinguish the adversity as less stressful, and employ adaptive behavioral and physiological responses (Franklin et al., 2012). For example, human subjects who secrete a greater amplitude of cortisol diurnally demonstrate lesser limbic activation (e.g., amygdala, hippocampus and hypothalamus) when exposed to stressful video images (Cunningham-Bussel et al., 2009). While C57BL6/J mice subjected to chronic social defeat can be separated into susceptible and resilient individuals based on their social interaction scores (Krishnan et al., 2007), selectively bred outbred Roman high- (RHA) and low-avoidance (RLA) rat sub-strains differ (RLA > RHA) in stress-evoked ACTH and corticosterone responses (Steimer and Driscoll, 2005). Similar to mammals, fishes exhibit pronounced intraspecies variability in stress responses (Demin et al., 2019; Volgin et al., 2019). For instance, less aggressive zebrafish with a reactive stress coping style display higher whole-body cortisol peaks than their bolder, proactive counterparts (Wong et al., 2019). Individually in zebrafish locomotion (e.g., high vs. low activity) is associated with differences in stress-related phenotypes, as female high-activity fish are less anxious than low-activity females (Tran and Gerlai, 2013). In addition, zebrafish also present individual differences in risk-taking behavior (e.g., predator inspection) between shy and bold individuals (Dugatkin et al., 2005). Collectively, this suggests a general conservation of stress resilient and vulnerability phenotypes across zebrafish and mammals. However, the exact evolutional role of such intraspecies variability remains unclear, and necessitates further studies. For instance, translational models of stress may benefit from targeting 'core' genetic and molecular elements of resilience/vulnerability phenotype represented simultaneously in all species. At the same time, recent study revealed no similarities between zebrafish, Atlantic salmon (*Salmo salar*) and European sea bass (*Dicentrarchus labrax*) in transcriptome signatures of their proactive behavior, highlighting some complication of cross-species studies of individual differences (Planellas et al., 2020).

There are also well-established strain and population differences in human stress responses (Miller and Kirschbaum, 2019). For instance, US and North European human subjects show lower cortisol stress responses and more severe depression then in some other European countries (e.g., Italy and Germany) (Kessler et al., 2015; Miller and Kirschbaum, 2019). Immobilization stress increases acoustic startle in Sprague–Dawley, but not Long–Evans rats (Faraday, 2002), whereas Fisher-344 rats show stress-related anhedonia, unlike more resilient Lewis rats (Ergang et al., 2015). Likewise, BALB/cJ mice are more vulnerable to stress, compared C57BL/6J (Razzoli et al., 2011) or SWR/J mice (Szklarczyk et al., 2012). In zebrafish, overt strain differences in stress responsivity also exist. For example, leopard, albino, AB and especially wild-derived strains considered to be highly sensitive to stress factors, whereas Tupfel long-fin (TL) and wild-type short-fin zebrafish are more resilient (Egan et al., 2009a; Kalueff et al., 2016a; Séguret et al., 2016; van den Bos et al., 2017a; van den Bos et al., 2017b; Vignet et al., 2013). The AB and TL zebrafish also differ in HPI axis activity (e.g., higher brain *crf*, *gr-beta*, *bdnf*, *pcna*, *neurod1*, *cart4*, *igf1* and *soc3a* expression) in both larvae and adult AB zebrafish (Gorissen et al., 2015; van den Bos et al., 2017a).

Laboratory zebrafish strains also differ markedly in behavior and stress responses from wild-caught or wild-derived (e.g., WIK) fish populations (Collier et al., 2017; Kalueff et al., 2016a). For instance, laboratory strain (e.g., TAB line) is less sensitive to stress evoked by a conspecific alarm substance exposure than wild (Ogwang, 2008). Leopard and albino strains present a high-anxiety in the novel tank test than wild-type zebrafish (Egan et al., 2009b). In addition, AB zebrafish had higher basal whole-body cortisol and lower inhibitory avoidance and shoal cohesion than TL zebrafish (Gorissen et al., 2015). Overall, these findings demonstrate that individual and strain differences in CNS stress responses are also seen across species, likely representing yet another shared, evolutionarily conserved aspect of animal stress responsivity.

6. Epigenetic modulations of stress response

In addition to physiological and CNS responses discussed above, stress also involves various epigenetic processes (e.g., DNA methylation, histone modification and microRNA activity) in the brain (Badyaev, 2005; Demin et al., 2020; Stankiewicz et al., 2013). For instance, human childhood trauma increases methylation of *NR3C1* (nuclear receptor subfamily 3 group member 1) gene (Van Der Knaap et al., 2014), whereas acute rodent predator stress increases the number of hippocampal neurons with phosphorylated serine 10 of histone 3 (H3) (Bilang-Bleuel et al., 2005). Acute restraint in rodents increases brain tri-methylation of H3 lysine 9 and reduces mono-methylation and tri-methylation of H3 lysine 27 (Hunter et al., 2009). Rodent chronic social defeat increases the acetylation of H3 lysine 9 and lysine 14 in neurons and glial (Hinwood et al., 2011), while chronic stress lowers medial PFC DNA methyltransferase 3a (*Dnmt3a*) mRNA expression, and hence a global DNA methylation (Elliott et al., 2016).

Zebrafish also represent a useful tool for studying brain epigenetic regulation during stress (Lakstygal et al., 2018). For instance, zebrafish exposure to acute severe stress upregulates CNS expression of several epigenetic genes, including *dnmt3a*, and *dnmt3b*, *hat1* (histone acetyltransferase 1) and *hdac4* (histone deacetylase) genes 10 days post-exposure (Yang et al., 2020). Paralleling this stress-induced upregulation of zebrafish *hdac4*, adult rats exposed to a single prolonged stressor (e.g., 2-h restraint + 20-min forced swim stress) also increase the number of HDAC4-expressing PFC and hippocampal neurons (Sailaja et al., 2012; Zhang et al., 2020). Taken together, these findings suggest that some epigenetic mechanisms induced by stress (e.g., upregulation of *HDAC4* by acute stressors) are similar across zebrafish and mammals, and hence may represent core, evolutionarily conserved molecular aspects of stress regulation in vertebrate CNS.

Notably, stress responsivity is also modulated transgenerationally. For example, parental life events impact behavior of rodent offspring, since F_1 from restrained (for 60 days) mothers and/or fathers show lower anxiety and serum cortisol and increased hippocampal mRNA expression of GR and BDNF than control F_1 offspring from unstressed parents (He et al., 2016). Similar behavioral and molecular changes are also observed in F_2 rodents (He et al., 2016). In humans, maternal cortisol affects the HPA axis function of the child, and may evoke their stress-related disorders later in life (Davis et al., 2007; Karlén et al., 2013; Oberlander et al., 2008). Similarly, maternal cortisol may also regulate the development of the fish HPI axis, subsequently impacting larval stress response (Nesan and Vijayan, 2016), because the role of maternal cortisol in neurogenesis and behavior of larval zebrafish has already been reported (Best et al., 2017). In zebrafish, larvae exposed for 6 days to fluoxetine (a selective serotonin reuptake inhibitor, SSRI) demonstrate lower cortisol levels in response to an acute stressor (e.g., net handling stressor) when adult (Vera-Chang et al., 2018). In addition, the suppression of stress response by fluoxetine persists for three consecutive generations in the unexposed descendants (Vera-Chang et al., 2018). Collectively, these findings demonstrate that while zebrafish (with an ex-uterus development) differ in developmental biology from mammals, behavioral and physiological effects of

Table 3
Summary of fish and mammalian brain areas (also see Fig. 1) involved in stress response, including the hypothalamus, brainstem, prosencephalic regions (e.g., prelimbic area and the prefrontal cortex), the amygdala and the hippocampus (Godoy et al., 2018; Schreck and Tort, 2016; Wendelaar Bonga, 1997b).

Mammalian brain part	Specific mammalian brain area	Fish homologs
Brainstem	Brainstem	Mesencephalon + rhombencephalon without the cerebellum
Cerebellum	Cerebellum	Cerebellum
Diencephalon	Hypothalamus	Hypothalamus
Forebrain		Telencephalon plus the diencephalon
	Pre-frontal cortex	[a]
	Amygdala	Amygdala/Dorsal telencephalon
	Hippocampus	Anterodorsolateral pallium/Dorsal telencephalon

[a] Absent in fish.

Table 4
Selected open questions related to the evolution of stress responses in fish and mammals.

Questions
Conceptual
• Do gene x environment correlations and interactions differentially shape stress responses between the taxa?
• What taxa (fish or mammals) are more resistant to epigenetic modulation of acute and chronic stress exposure?
• How does the absence of neocortex in fish affect the difference in response to stress between mammals and fish?
• What are the neurobiological mechanisms and circuits involved in each type of stressor (e.g., physical vs. physiological) in fish?
• How much the human and animal personality is influence by stress axis?
Methodological
• Are there any other stress responses in fishes that may be additionally used, similarly to rodents grooming?
• Are there any similarities between mechanisms underlying individual variation in stress responses in different taxa?
• Do differences in stress-related genes reflect the types of stressors that face different species?
• What is the environment (e.g., laboratory vs. natural habitat) that most quickly impacts for evolutionary modulation of the stress axis in animal models?
• How the environment can impact for the development of stress-related disorders?
• What are the mechanisms involved in the development of stress-related disorders in each type of environment (e.g., laboratory vs. natural habitat)?
• Can highly variable laboratory housing conditions contribute to behavioral and physiological variance in animal stress models?

parenteral exposure to stress or drugs and their transgenerational consequences may be rather similar to mammals.

7. Conclusion

Mounting evidence summarized here, including homologous stress-related genes (Table 2), similar behaviors, overlapping brain anatomy (Fig. 1, Table 3) and shared epigenetic modulation, supports common, evolutionarily conserved mechanisms of various CNS stress responses in fish and mammals. Recognizing such common natural evolution across vertebrate taxa, our understanding how stress response has evolved across species may help develop more effective pharmacological and non-pharmacological therapies for various stress-related disorders (e.g., PTSD or depression). In addition, this knowledge may foster the development of more robust animal experimental models to assess stress-related disorders, as well as their potential epigenetic modulation.

However, some methodological limitations of animal experimental models of stress must also be considered. For instance, rodent stress-related behaviors are greatly influenced by extrinsic factors, such as experimenter identity (Katsnelson, 2014), as rodents manipulated by male (but not female) experimenters display reduced nociception (Sorge et al., 2014). In contrast, experimenter sex does not affect zebrafish anxiety assays, such as the novel tank and the light-dark tests (de Abreu and Kalueff, 2021; Lieggi et al., 2020; Stewart et al., 2015). Thus, fish models and tests may provide a higher reproducibility and replicability of data in stress studies, being less influenced by common environmental factors (de Abreu and Kalueff, 2021).

Moreover, fish models also present some additional, fish-specific limitations. For example, fishes live in the aquatic environment, where stress hormones and other substances are constantly secreted (via urine/feces) by fish (Vermeirssen and Scott, 1996) and other animals and humans (Calisto and Esteves, 2009). Thus, unlike rodents, fish may continuously absorb and bioaccumulate these substances (Brodin et al., 2013), likely to play an important role in stress axis modulation. In addition, zebrafish may not experience stress-induce hyperthermia, as in rodents and humans (Jones et al., 2019). Finally, as many outstanding questions regarding the evolution of stress responses in fish and mammals remain open (Table 4), addressing them in future translational cross-species studies may improve our understanding of the natural evolution of stress responses in animal kingdom.

CRediT authorship contribution statement

Murilo S. de Abreu: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Konstantin A. Demin:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Ana C.V.V. Giacomini:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Tamara G. Amstislavskaya:** Writing – original draft, Writing – review & editing. **Tatyana Strekalova:** Writing – original draft, Writing – review & editing. **Gleb O. Maslov:** Writing – original draft, Writing – review & editing. **Yury Kositsin:** Writing – original draft, Writing – review & editing. **Elena V. Petersen:** Writing – original draft, Writing – review & editing. **Allan V. Kalueff:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare no conflicts of interest.

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References

Abreu, M.S., Giacomini, A., Koakoski, G., Piato, A.L.S., Barcellos, L.J.G., 2017. Divergent effect of fluoxetine on the response to physical or chemical stressors in zebrafish. PeerJ 5, 10.
Abreu, M.S., Giacomini, A.C.V., Koakoski, G., Oliveira, T.A., Gusso, D., Baldisserotto, B., Barcellos, L.J.G., 2015. Effects of waterborne fluoxetine on stress response and osmoregulation in zebrafish. Environ. Toxicol. Pharmacol. 40, 704–707.
Alsop, D., Vijayan, M., 2009. The zebrafish stress axis: molecular fallout from the teleost-specific genome duplication event. Gen. Comp. Endocrinol. 161, 62–66.
Alsop, D., Vijayan, M.M., 2008. Development of the corticosteroid stress axis and receptor expression in zebrafish. Am. J. Physiol. Regul. Integr. Comp. Physiol. 294, R711–R719.
Andersen, S.L., Lyss, P.J., Dumont, N.L., Teicher, M.H., 1999. Enduring neurochemical effects of early maternal separation on limbic structures. Ann. N. Y. Acad. Sci. 877, 756–759.
Andresen, N., Wöllhaf, M., Hohlbaum, K., Lewejohann, L., Hellwich, O., Thöne-Reineke, C., Belik, V., 2020. Towards a fully automated surveillance of well-being status in laboratory mice using deep learning: starting with facial expression analysis. PloS One 15, e0228059.

Anneser, L., Alcantara, I.C., Gemmer, A., Mirkes, K., Ryu, S., Schuman, E.M., 2020. The neuropeptide Pth2 dynamically senses others via mechanosensation. Nature 1–5.
Aponte, A., Petrunich-Rutherford, M.L., 2019. Acute net stress of young adult zebrafish (Danio rerio) is not sufficient to increase anxiety-like behavior and whole-body cortisol. PeerJ 7 e7469-e7469.
Arends, R.J., Vermeer, H., Martens, G.J.M., Leunissen, J.A.M., Wendelaar Bonga, S.E., Flik, G., 1998. Cloning and expression of two proopiomelanocortin mRNAs in the common carp (Cyprinus carpio L.). Mol. Cell. Endocrinol. 143, 23–31.
Badyaev, A.V., 2005. Stress-induced variation in evolution: from behavioural plasticity to genetic assimilation. Proceedings. Biological sciences 272, 877–886.
Bangasser, D.A., Valentino, R.J., 2014. Sex differences in stress-related psychiatric disorders: neurobiological perspectives. Front. Neuroendocrinol. 35, 303–319.
Bangasser, D.A., Wicks, B., 2017. Sex-specific mechanisms for responding to stress. J. Neurosci. Res. 95, 75–82.
Barcellos, L.J.G., Nicolaiewsky, S., De Souza, S.M.G., Lulhier, F., 1999. The effects of stocking density and social interaction on acute stress response in Nile tilapia Oreochromis niloticus (L.) fingerlings. Aquacult. Res. 30, 887–892.
Barreto, R.E., Volpato, G.L., 2006. Stress responses of the fish Nile tilapia subjected to electroshock and social stressors. Braz. J. Med. Biol. Res. 39, 1605–1612.
Barton, B.A., 2000. Salmonid fishes differ in their cortisol and glucose responses to handling and transport stress. N. Am. J. Aquacult. 62, 12–18.
Barton, B.A., Bollig, H., Hauskins, B.L., Jansen, C.R., 2000. Juvenile pallid (Scaphirhynchus albus) and hybrid pallid×shovelnose (S. albus×platorynchus) sturgeons exhibit low physiological responses to acute handling and severe confinement. Comp. Biochem. Physiol. Mol. Integr. Physiol. 126, 125–134.
Barton, B.A., Iwama, G.K., 1991. Physiological changes in fish from stress in aquaculture with emphasis on the response and effects of corticosteroids. Annu. Rev. Fish Dis. 1, 3–26.
Beery, A.K., Kaufer, D., 2015. Stress, social behavior, and resilience: insights from rodents. Neurobiology of stress 1, 116–127.
Best, C., Kurrasch, D.M., Vijayan, M.M., 2017. Maternal cortisol stimulates neurogenesis and affects larval behaviour in zebrafish. Sci. Rep. 7, 40905.
Bhat, M.S., Rao, G., Murthy, K.D., Bhat, P.G., 2007. Housing in pyramid counteracts neuroendocrine and oxidative stress caused by chronic restraint in rats. Evid Based Complement Alternat Med 4, 35–42.
Bilang-Bleuel, A., Ulbricht, S., Chandramohan, Y., De Carli, S., Droste, S.K., Reul, J.M.H. M., 2005. Psychological stress increases histone H3 phosphorylation in adult dentate gyrus granule neurons: involvement in a glucocorticoid receptor-dependent behavioural response. Eur. J. Neurosci. 22, 1691–1700.
Bondar, N.P., Lepeshko, A.A., Reshetnikov, V.V., 2018. Effects of early-life stress on social and anxiety-like behaviors in adult mice: sex-specific effects. Behav. Neurol. 2018, 1538931-1538931.
Brecht, M., Freiwald, W.A., 2012. The many facets of facial interactions in mammals. Curr. Opin. Neurobiol. 22, 259–266.
Bremner, J.D., Narayan, M., Anderson, E.R., Staib, L.H., Miller, H.L., Charney, D.S., 2000. Hippocampal volume reduction in major depression. Am. J. Psychiatr. 157, 115–118.
Brodin, T., Fick, J., Jonsson, M., Klaminder, J., 2013. Dilute concentrations of a psychiatric drug alter behavior of fish from natural populations. Science 339, 814–815.
Brown, K.J., Grunberg, N.E., 1995. Effects of housing on male and female rats: crowding stresses males but calms females. Physiol. Behav. 58, 1085–1089.
Brunoni, A.R., Lopes, M., Fregni, F., 2008. A systematic review and meta-analysis of clinical studies on major depression and BDNF levels: implications for the role of neuroplasticity in depression. Int. J. Neuropsychopharmacol. 11, 1169–1180.
Burrows, A.M., Waller, B.M., Parr, L.A., Bonar, C.J., 2006. Muscles of facial expression in the chimpanzee (Pan troglodytes): descriptive, comparative and phylogenetic contexts. J. Anat. 208, 153–167.
Calisto, V., Esteves, V.I., 2009. Psychiatric pharmaceuticals in the environment. Chemosphere 77, 1257–1274.
Campos, A.C., Fogaça, M.V., Aguiar, D.C., Guimaraes, F.S., 2013. Animal models of anxiety disorders and stress. Brazilian Journal of Psychiatry 35, S101–S111.
Carey, J.B., McCormick, S.D., 1998. Atlantic salmon smolts are more responsive to an acute handling and confinement stress than parr. Aquaculture 168, 237–253.
Carlson, E.B., Rosser-Hogan, R., 1991. Trauma experiences, posttraumatic stress, dissociation, and depression in Cambodian refugees. Am. J. Psychiatr. 148, 1548.
Cericato, L., Neto, J.G.M., Fagundes, M., Kreutz, L.C., Quevedo, R.M., Finco, J., da Rosa, J.G.S., Koakoski, G., Centenaro, L., Pottker, E., Anziliero, D., Barcellos, L.J.G., 2008. Cortisol response to acute stress in jundiá Rhamdia quelen acutely exposed to sub-lethal concentrations of agrichemicals. Comp. Biochem. Physiol. C Toxicol. Pharmacol. 148, 281–286.
Chang, A.C., Cochet, M., Cohen, S.N., 1980. Structural organization of human genomic DNA encoding the pro-opiomelanocortin peptide. Proc. Natl. Acad. Sci. U. S. A. 77, 4890–4894.
Chen, Z.-Y., Jing, D., Bath, K.G., Ieraci, A., Khan, T., Siao, C.-J., Herrera, D.G., Toth, M., Yang, C., McEwen, B.S., Hempstead, B.L., Lee, F.S., 2006. Genetic variant BDNF (Val66Met) polymorphism alters anxiety-related behavior. Science (New York, N.Y.) 314, 140–143.
Christian, J.J., 1971. Population density and reproductive efficiency. Biol. Reprod. 4, 248–294.
Cohen, S., Janicki-Deverts, D., Miller, G.E., 2007. Psychological stress and disease. Jama 298, 1685–1687.
Cohen, S., Williamson, G.M., 1991. Stress and infectious disease in humans. Psychol. Bull. 109, 5.
Collier, A.D., Kalueff, A.V., Echevarria, D.J., 2017. Zebrafish Models of Anxiety-like Behaviors. In: Kalueff, A.V. (Ed.), The Rights and Wrongs of Zebrafish: Behavioral Phenotyping of Zebrafish. Springer International Publishing, Cham, pp. 45–72.
Conrad, C.D., 2008. Chronic stress-induced hippocampal vulnerability: the glucocorticoid vulnerability hypothesis. Rev. Neurosci. 19, 395–412.
Cullinan, W.E., Herman, J.P., Battaglia, D.F., Akil, H., Watson, S.J., 1995. Pattern and time course of immediate early gene expression in rat brain following acute stress. Neuroscience 64, 477–505.
Cunningham-Bussel, A.C., Root, J.C., Butler, T., Tuescher, O., Pan, H., Epstein, J., Weisholtz, D.S., Pavony, M., Silverman, M.E., Goldstein, M.S., Altemus, M., Cloitre, M., LeDoux, J., McEwen, B., Stern, E., Silbersweig, D., 2009. Diurnal cortisol amplitude and fronto-limbic activity in response to stressful stimuli. Psychoneuroendocrinology 34, 694–704.
Davis, E.P., Glynn, L.M., Schetter, C.D., Hobel, C., Chicz-Demet, A., Sandman, C.A., 2007. Prenatal exposure to maternal depression and cortisol influences infant temperament. J. Am. Acad. Child Adolesc. Psychiatry 46, 737–746.
Dayas, C.V., Buller, K.M., Crane, J.W., Xu, Y., Day, T.A., 2001. Stressor categorization: acute physical and psychological stressors elicit distinctive recruitment patterns in the amygdala and in medullary noradrenergic cell groups. Eur. J. Neurosci. 14, 1143–1152.
de Abreu, M.S., Demin, K.A., Amstislavskaya, T.G., Strekalova, T., Kalueff, A.V., 2021. Chapter 23 - Zebrafish Models for Stress Research. In: Fink, G. (Ed.), Stress: Genetics, Epigenetics and Genomics. Academic Press, pp. 263–268.
de Abreu, M.S., Kalueff, A.V., 2021. Of mice and zebrafish: the impact of the experimenter identity on animal behavior. Lab. Anim. 50, 7-7.
de Abreu, M.S., Koakoski, G., Ferreira, D., Oliveira, T.A., da Rosa, J.G.S., Gusso, D., Giacomini, A.C.V., Piato, A.L., Barcellos, L.J.G., 2014. Diazepam and fluoxetine decrease the stress response in zebrafish. PloS One 9, 5.
De Kloet, E.R., Joëls, M., Holsboer, F., 2005. Stress and the brain: from adaptation to disease. Nat. Rev. Neurosci. 6, 463–475.
Deltheil, T., Tanaka, K., Reperant, C., Hen, R., David, D.J., Gardier, A.M., 2009. Synergistic neurochemical and behavioural effects of acute intrahippocampal injection of brain-derived neurotrophic factor and antidepressants in adult mice. Int. J. Neuropsychopharmacol. 12, 905–915.
Demin, K.A., Lakstygal, A.M., Alekseeva, P.A., Sysoev, M., de Abreu, M.S., Alpyshov, E. T., Serikuly, N., Wang, D., Wang, M., Tang, Z., 2019. The role of intraspecies variation in fish neurobehavioral and neuropharmacological phenotypes in aquatic models. Aquat. Toxicol. 210, 44–55.
Demin, K.A., Taranov, A.S., Ilyin, N.P., Lakstygal, A.M., Volgin, A.D., de Abreu, M.S., Strekalova, T., Kalueff, A.V., 2020. Understanding neurobehavioral effects of acute and chronic stress in zebrafish. Stress, 1-48.
Devaud, L., Johnson, H., Lally, J., Perez, E., 2019. Sex differences in anxiety-like behaviors following chronic intermittent ethanol and/or repeated stress exposures using an adult zebrafish (Danio rerio) model. Faseb. J. 33, 499.491-499.491.
Diorio, D., Viau, V., Meaney, M.J., 1993. The role of the medial prefrontal cortex (cingulate gyrus) in the regulation of hypothalamic-pituitary-adrenal responses to stress. J. Neurosci. 13, 3839–3847.
Dugatkin, L.A., McCall, M.A., Gregg, R.G., Cavanaugh, A., Christensen, C., Unseld, M., 2005. Zebrafish (Danio rerio) exhibit individual differences in risk-taking behavior during predator inspection. Ethol. Ecol. Evol. 17, 77–81.
Duman, R.S., Monteggia, L.M., 2006. A neurotrophic model for stress-related mood disorders. Biol. Psychiatr. 59, 1116–1127.
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., 2009a. Understanding behavioral and physiological phenotypes of stress and anxiety in zebrafish. Behav. Brain Res. 205, 38–44.
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., Mohnot, S., Beeson, E., Glasgow, E., Amri, H., Zukowska, Z., Kalueff, A.V., 2009b. Understanding behavioral and physiological phenotypes of stress and anxiety in zebrafish. Behav. Brain Res. 205, 38–44.
Elliott, E., Manashirov, S., Zwang, R., Gil, S., Tsoory, M., Shemesh, Y., Chen, A., 2016. Dnmt3a in the medial prefrontal cortex regulates anxiety-like behavior in adult mice. J. Neurosci. 36, 730–740.
Ergang, P., Vodička, M., Soták, M., Klusoňová, P., Behuliak, M., Řeháková, L., Zach, P., Pácha, J., 2015. Differential impact of stress on hypothalamic–pituitary–adrenal axis: gene expression changes in Lewis and Fisher rats. Psychoneuroendocrinology 53, 49–59.
Eto, K., Mazilu-Brown, J.K., Henderson-MacLennan, N., Dipple, K.M., McCabe, E.R.B., 2014. Development of catecholamine and cortisol stress responses in zebrafish. Molecular Genetics and Metabolism Reports 1, 373–377.
Evans, J.R., Torres-Pérez, J.V., Petrazzini, M.E.M., Riley, R., Brennan, C.H., 2021. Stress reactivity elicits a tissue-specific reduction in telomere length in aging zebrafish (Danio rerio). Sci. Rep. 11, 1–11.
Faraday, M.M., 2002. Rat sex and strain differences in responses to stress. Physiol. Behav. 75, 507–522.
Fenoglio, K.A., Brunson, K.L., Baram, T.Z., 2006. Hippocampal neuroplasticity induced by early-life stress: functional and molecular aspects. Front. Neuroendocrinol. 27, 180–192.
Figueiredo, H.F., Bodie, B.L., Tauchi, M., Dolgas, C.M., Herman, J.P., 2003a. Stress integration after acute and chronic predator stress: differential activation of central stress circuitry and sensitization of the hypothalamo-pituitary-adrenocortical axis. Endocrinology 144, 5249–5258.
Figueiredo, H.F., Bruestle, A., Bodie, B., Dolgas, C.M., Herman, J.P., 2003b. The medial prefrontal cortex differentially regulates stress-induced c-fos expression in the forebrain depending on type of stressor. Eur. J. Neurosci. 18, 2357–2364.

Finnell, J.E., Lombard, C.M., Padi, A.R., Moffitt, C.M., Wilson, L.B., Wood, C.S., Wood, S. K., 2017. Physical versus psychological social stress in male rats reveals distinct cardiovascular, inflammatory and behavioral consequences. PloS One 12 e0172868-e0172868.
Finsterwald, 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.
Flurkey, K.C.J., Harrison, D.E., 2007. The mouse in aging research. Burlington: American College Laboratory Animal Medicine (Elsevier).
Fontana, B.D., Cleal, M., Parker, M.O., 2019. Female adult zebrafish (Danio rerio) show higher levels of anxiety-like behavior than males, but do not differ in learning and memory capacity. European Journal of Neuroscience n/a.
Fontana, B.D., Müller, T.E., Cleal, M., de Abreu, M.S., Norton, W.H.J., Demin, K.A., Amstislavskaya, T.G., Petersen, E.V., Kalueff, A.V., Parker, M.O., Rosemberg, D.B., 2021. Using zebrafish (Danio rerio) models to understand the critical role of social interactions in mental health and wellbeing. Prog. Neurobiol., 101993
Franklin, T.B., Saab, B.J., Mansuy, I.M., 2012. Neural mechanisms of stress resilience and vulnerability. Neuron 75, 747–761.
Gabbott, P.L.A., Warner, T.A., Jays, P.R.L., Salway, P., Busby, S.J., 2005. Prefrontal cortex in the rat: projections to subcortical autonomic, motor, and limbic centers. J. Comp. Neurol. 492, 145–177.
Gallo-Payet, N., Battista, M.C., 2011. Steroidogenesis—adrenal cell signal transduction. Comp. Physiol. 4, 889–964.
Geerling, J.C., Shin, J.W., Chimenti, P.C., Loewy, A.D., 2010. Paraventricular hypothalamic nucleus: axonal projections to the brainstem. J. Comp. Neurol. 518, 1460–1499.
Genario, R., Giacomini, A.C.V.V., de Abreu, M.S., Marcon, L., Demin, K.A., Kalueff, A.V., 2020. Sex differences in adult zebrafish anxiolytic-like responses to diazepam and melatonin. Neurosci. Lett. 714, 134548.
Gensure, R.C., Ponugoti, B., Gunes, Y., Papasani, M.R., Lanske, B., Bastepe, M., Rubin, D. A., Jüppner, H., 2004. Identification and characterization of two parathyroid hormone-like molecules in zebrafish. Endocrinology 145, 1634–1639.
Ghisleni, G., Capiotti, K.M., Da Silva, R.S., Oses, J.P., Piato, Â., Soares, V., Bogo, M.R., Bonan, C.D., 2012. The role of CRH in behavioral responses to acute restraint stress in zebrafish. Prog. Neuro-Psychopharmacol. Biol. Psychiatry 36, 176–182.
Giacomini, A.C., de Abreu, M.S., Koakoski, G., Idalencio, R., Kalichak, F., Oliveira, T.A., da Rosa, J.G., Gusso, D., Piato, A.L., Barcellos, L.J., 2015. My stress, our stress: blunted cortisol response to stress in isolated housed zebrafish. Physiol. Behav. 139, 182–187.
Godoy, L.D., Rossignoli, M.T., Delfino-Pereira, P., Garcia-Cairasco, N., de Lima Umeoka, E.H., 2018. A comprehensive overview on stress neurobiology: basic concepts and clinical implications. Front. Behav. Neurosci. 12, 127.
Gong, S., Miao, Y.-L., Jiao, G.-Z., Sun, M.-J., Li, H., Lin, J., Luo, M.-J., Tan, J.-H., 2015. Dynamics and correlation of serum cortisol and corticosterone under different physiological or stressful conditions in mice. PloS One 10 e0117503-e0117503.
Gonzalez-Nunez, V., Gonzalez-Sarmiento, R., Rodriguez, R.E., 2003. Identification of two proopiomelanocortin genes in zebrafish (Danio rerio). Brain Res Mol Brain Res 120, 1–8.
Gorissen, M., Manuel, R., Pelgrim, T.N.M., Mes, W., de Wolf, M.J.S., Zethof, J., Flik, G., van den Bos, R., 2015. Differences in inhibitory avoidance, cortisol and brain gene expression in TL and AB zebrafish. Gene Brain Behav. 14, 428–438.
Gourley, S.L., Kiraly, D.D., Howell, J.L., Olausson, P., Taylor, J.R., 2008. Acute hippocampal brain-derived neurotrophic factor restores motivational and forced swim performance after corticosterone. Biol. Psychiatr. 64, 884–890.
Grandel, H., Kaslin, J., Ganz, J., Wenzel, I., Brand, M., 2006. Neural stem cells and neurogenesis in the adult zebrafish brain: origin, proliferation dynamics, migration and cell fate. Dev. Biol. 295, 263–277.
Gunnar, M.R., Wewerka, S., Frenn, K., Long, J.D., Griggs, C., 2009. Developmental changes in hypothalamus-pituitary-adrenal activity over the transition to adolescence: normative changes and associations with puberty. Dev. Psychopathol. 21, 69–85.
Gutchess, A., Alves, A.N., Paige, L.E., Rohleder, N., Wolf, J.M., 2019. Age differences in the relationship between cortisol and emotional memory. Psychol. Aging 34, 655–664.
Handa, R.J., Burgess, L.H., Kerr, J.E., O'Keefe, J.A., 1994. Gonadal steroid hormone receptors and sex differences in the hypothalamo-pituitary-adrenal axis. Horm. Behav. 28, 464–476.
Hatch, A.M., Wiberg, G.S., Zawidzka, Z., Cann, M., Airth, J.M., Grice, H.C., 1965. Isolation syndrome in the rat. Toxicol. Appl. Pharmacol. 7, 737–745.
Hawley, J.M., Keevil, B.G., 2016. Endogenous glucocorticoid analysis by liquid chromatography–tandem mass spectrometry in routine clinical laboratories. J. Steroid Biochem. Mol. Biol. 162, 27–40.
He, N., Kong, Q.-Q., Wang, J.-Z., Ning, S.-F., Miao, Y.-L., Yuan, H.-J., Gong, S., Cui, X.-Z., Li, C.-Y., Tan, J.-H., 2016. Parental life events cause behavioral difference among offspring: adult pre-gestational restraint stress reduces anxiety across generations. Sci. Rep. 6, 1–12.
Heinzelmann, M., Gill, J., 2013. Epigenetic mechanisms shape the biological response to trauma and risk for PTSD: a critical review. Nursing research and practice 2013.
Herman, J.P., Figueiredo, H., Mueller, N.K., Ulrich-Lai, Y., Ostrander, M.M., Choi, D.C., Cullinan, W.E., 2003. Central mechanisms of stress integration: hierarchical circuitry controlling hypothalamo–pituitary–adrenocortical responsiveness. Front. Neuroendocrinol. 24, 151–180.
Herman, J.P., Ostrander, M.M., Mueller, N.K., Figueiredo, H., 2005. Limbic system mechanisms of stress regulation: hypothalamo-pituitary-adrenocortical axis. Prog. Neuro Psychopharmacol. Biol. Psychiatr. 29, 1201–1213.
Higuchi, M., 2020. Maternal stress suppresses cell proliferation in the forebrain of zebrafish larvae. Gene Cell. 25, 350–357.
Hinwood, M., Tynan, R.J., Day, T.A., Walker, F.R., 2011. Repeated social defeat selectively increases δFosB expression and histone H3 acetylation in the infralimbic medial prefrontal cortex. Cerebr. Cortex 21, 262–271.
Hogan, B.M., Danks, J.A., Layton, J.E., Hall, N.E., Heath, J.K., Lieschke, G.J., 2005. Duplicate zebrafish pth genes are expressed along the lateral line and in the central nervous system during embryogenesis. Endocrinology 146, 547–551.
Howe, K., Clark, M.D., Torroja, C.F., Torrance, J., Berthelot, C., Muffato, M., Collins, J.E., Humphray, S., McLaren, K., Matthews, L., McLaren, S., Sealy, I., Caccamo, M., Churcher, C., Scott, C., Barrett, J.C., Koch, R., Rauch, G.J., White, S., Chow, W., Kilian, B., Quintais, L.T., Guerra-Assunção, J.A., Zhou, Y., Gu, Y., Yen, J., Vogel, J.H., Eyre, T., Redmond, S., Banerjee, R., Chi, J., Fu, B., Langley, E., Maguire, S.F., Laird, G.K., Lloyd, D., Kenyon, E., Donaldson, S., Sehra, H., Almeida-King, J., Loveland, J., Trevanion, S., Jones, M., Quail, M., Willey, D., Hunt, A., Burton, J., Sims, S., McLay, K., Plumb, B., Davis, J., Clee, C., Oliver, K., Clark, R., Riddle, C., Elliot, D., Eliott, D., Threadgold, G., Harden, G., Ware, D., Begum, S., Mortimore, B., Mortimer, B., Kerry, G., Heath, P., Phillimore, B., Tracey, A., Corby, N., Dunn, M., Johnson, C., Wood, J., Clark, S., Pelan, S., Griffiths, G., Smith, M., Glithero, R., Howden, P., Barker, N., Lloyd, C., Stevens, C., Harley, J., Holt, K., Panagiotidis, G., Lovell, J., Beasley, H., Henderson, C., Gordon, D., Auger, K., Wright, D., Collins, J., Raisen, C., Dyer, L., Leung, K., Robertson, L., Ambridge, K., Leongamornlert, D., McGuire, S., Gilderthorp, R., Griffiths, C., Manthravadi, D., Nichol, S., Barker, G., Whitehead, S., Kay, M., Brown, J., Murnane, C., Gray, E., Humphries, M., Sycamore, N., Barker, D., Saunders, D., Wallis, J., Babbage, A., Hammond, S., Mashreghi-Mohammadi, M., Barr, L., Martin, S., Wray, P., Ellington, A., Matthews, N., Ellwood, M., Woodmansey, R., Clark, G., Cooper, J., Tromans, A., Grafham, D., Skuce, C., Pandian, R., Andrews, R., Harrison, E., Kimberley, A., Garnett, J., Fosker, N., Hall, R., Garner, P., Kelly, D., Bird, C., Palmer, S., Gehring, I., Berger, A., Dooley, C.M., Ersan-Ürün, Z., Eser, C., Geiger, H., Geisler, M., Karotki, L., Kirn, A., Konantz, J., Konantz, M., Oberländer, M., Rudolph-Geiger, S., Teucke, M., Lanz, C., Raddatz, G., Osoegawa, K., Zhu, B., Rapp, A., Widaa, S., Langford, C., Yang, F., Schuster, S.C., Carter, N.P., Harrow, J., Ning, Z., Herrero, J., Searle, S.M., Enright, A., Geisler, R., Plasterk, R.H., Lee, C., Westerfield, M., de Jong, P.J., Zon, L. I., Postlethwait, J.H., Nüsslein-Volhard, C., Hubbard, T.J., Roest Crollius, H., Rogers, J., Stemple, D.L., 2013. The zebrafish reference genome sequence and its relationship to the human genome. Nature 496, 498–503.
Hu, J., Feng, B., Zhu, Y., Wang, W., Xie, J., Zheng, X., 2017. Gender Differences in PTSD: Susceptibility and Resilience, Gender Differences in Different Contexts. BoD–Books on Demand, pp. 21–42.
Hunter, R.G., McCarthy, K.J., Milne, T.A., Pfaff, D.W., McEwen, B.S., 2009. Regulation of hippocampal H3 histone methylation by acute and chronic stress. Proc. Natl. Acad. Sci. Unit. States Am. 106, 20912–20917.
Idler, D.R., Freeman, H.C., 1968. Binding of testosterone, 1α-hydroxycorticosterone and cortisol by plasma proteins of fish. Gen. Comp. Endocrinol. 11, 366–372.
Inoue, L.A.K.A., MorAes, G., IwAma, G.K., Afonso, L.O.B., 2008. Physiological stress responses in the warm-water fish matrinxã (Brycon amazonicus) subjected to a sudden cold shock. Acta Amazonica 38, 603–609.
Janak, P.H., Tye, K.M., 2015. From circuits to behaviour in the amygdala. Nature 517, 284–292.
Joëls, M., Baram, T.Z., 2009. The neuro-symphony of stress. Nat. Rev. Neurosci. 10, 459.
Joëls, M., Karst, H., Sarabdjitsingh, R.A., 2018. The stressed brain of humans and rodents. Acta Physiol. 223 e13066-e13066.
Joëls, M., Sarabdjitsingh, R.A., Karst, H., 2012. Unraveling the time domains of corticosteroid hormone influences on brain activity: rapid, slow, and chronic modes. Pharmacol. Rev. 64, 901–938.
Johansson, L., Guo, X., Waern, M., Östling, S., Gustafson, D., Bengtsson, C., Skoog, I., 2010. Midlife psychological stress and risk of dementia: a 35-year longitudinal population study. Brain 133, 2217–2224.
Jones, N.A.R., Mendo, T., Broell, F., Webster, M.M., 2019. No experimental evidence of stress-induced hyperthermia in zebrafish (Danio rerio). J. Exp. Biol. 222.
Kalueff, A.V., Echevarria, D.J., Homechaudhuri, S., Stewart, A.M., Collier, A.D., Kaluyeva, A.A., Li, S., Liu, Y., Chen, P., Wang, J., Yang, L., Mitra, A., Pal, S., Chaudhuri, A., Roy, A., Biswas, M., Roy, D., Podder, A., Poudel, M.K., Katare, D.P., Mani, R.J., Kyzar, E.J., Gaikwad, S., Nguyen, M., Song, C., 2016a. Zebrafish neurobehavioral phenomics for aquatic neuropharmacology and toxicology research. Aquat. Toxicol. 170, 297–309.
Kalueff, A.V., Echevarria, D.J., Stewart, A.M., 2014a. Gaining translational momentum: more zebrafish models for neuroscience research. Prog. Neuro Psychopharmacol. Biol. Psychiatr. 55, 1–6.
Kalueff, A.V., Stewart, A.M., Gerlai, R., 2014b. Zebrafish as an emerging model for studying complex brain disorders. Trends Pharmacol. Sci. 35, 63–75.
Kalueff, A.V., Stewart, A.M., Song, C., Berridge, K.C., Graybiel, A.M., Fentress, J.C., 2016b. Neurobiology of rodent self-grooming and its value for translational neuroscience. Nat. Rev. Neurosci. 17, 45–59.
Karege, F., Perret, G., Bondolfi, G., Schwald, M., Bertschy, G., Aubry, J.M., 2002. Decreased serum brain-derived neurotrophic factor levels in major depressed patients. Psychiatr. Res. 109, 143–148.
Karlén, J., Frostell, A., Theodorsson, E., Faresjö, T., Ludvigsson, J., 2013. Maternal influence on child HPA Axis: a prospective study of cortisol levels in hair. Pediatrics 132, E1333–E1340.
Kaslin, J., Ganz, J., Brand, M., 2008. Proliferation, neurogenesis and regeneration in the non-mammalian vertebrate brain. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 363, 101–122.
Katsnelson, A., 2014. Male researchers stress out rodents. Nature News.

Katsu, Y., Iguchi, T., 2016. Subchapter 95D - Cortisol. In: Takei, Y., Ando, H., Tsutsui, K. (Eds.), Handbook of Hormones. Academic Press, San Diego, 533-e595D-532.
Kessler, R.C., Sampson, N.A., Berglund, P., Gruber, M.J., Al-Hamzawi, A., Andrade, L., Bunting, B., Demyttenaere, K., Florescu, S., De Girolamo, G., 2015. Anxious and non-anxious major depressive disorder in the world health organization world mental health surveys. Epidemiol. Psychiatr. Sci. 24, 210–226.
Khan, K.M., Collier, A.D., Meshalkina, D.A., Kysil, E.V., Khatsko, S.L., Kolesnikova, T., Morzherin, Y.Y., Warnick, J.E., Kalueff, A.V., Echevarria, D.J., 2017. Zebrafish models in neuropsychopharmacology and CNS drug discovery. Br. J. Pharmacol. 174, 1925–1944.
Kirsten, K., Pompermaier, A., Koakoski, G., Mendonça-Soares, S., da Costa, R.A., Maffi, V. C., Kreutz, L.C., Barcellos, L.J.G., 2020. Acute and chronic stress differently alter the expression of cytokine and neuronal markers genes in zebrafish brain. Stress 1–6.
Kishi, S., Slack, B.E., Uchiyama, J., Zhdanova, I.V., 2009. Zebrafish as a genetic model in biological and behavioral gerontology: where development meets aging in vertebrates–a mini-review. Gerontology 55, 430–441.
Kitay, J.I., 1961. Sex differences in adrenal cortical secretion in the rat. Endocrinology 68, 818–824.
Kotrschal, A., Ilmonen, P., Penn, D.J., 2007. Stress impacts telomere dynamics. Biol. Lett. 3, 128–130.
Krishnan, V., Han, M.H., Graham, D.L., Berton, O., Renthal, W., Russo, S.J., Laplant, Q., Graham, A., Lutter, M., Lagace, D.C., Ghose, S., Reister, R., Tannous, P., Green, T.A., Neve, R.L., Chakravarty, S., Kumar, A., Eisch, A.J., Self, D.W., Lee, F.S., Tamminga, C.A., Cooper, D.C., Gershenfeld, H.K., Nestler, E.J., 2007. Molecular adaptations underlying susceptibility and resistance to social defeat in brain reward regions. Cell 131, 391–404.
Kulle, A.E., Welzel, M., Holterhus, P.-M., Riepe, F.G., 2013. Implementation of a liquid chromatography tandem mass spectrometry assay for eight adrenal C-21 steroids and pediatric reference data. Hormone research in paediatrics 79, 22–31.
Lakstygal, A.M., de Abreu, M.S., Kalueff, A.V., 2018. Zebrafish models of epigenetic regulation of CNS functions. Brain Res. Bull. 142, 344–351.
Langford, D.J., Bailey, A.L., Chanda, M.L., Clarke, S.E., Drummond, T.E., Echols, S., Glick, S., Ingrao, J., Klassen-Ross, T., LaCroix-Fralish, M.L., 2010. Coding of facial expressions of pain in the laboratory mouse. Nat. Methods 7, 447–449.
Larsson, C.A., Gullberg, B., Råstam, L., Lindblad, U., 2009. Salivary cortisol differs with age and sex and shows inverse associations with WHR in Swedish women: a cross-sectional study. BMC Endocr. Disord. 9, 16.
LederiS, K., Fryer, J.N., Okawara, Y., Schönrock, C., Richter, D., 1994. 2 Corticotropin-Releasing Factors Acting on the Fish Pituitary: Experimental and Molecular Analysis. In: Sherwood, N.M., Hew, C.L., Farrell, A.P., Randall, D.J. (Eds.), Fish Physiology. Academic Press, pp. 67–100.
LeDoux, J., 2007. The amygdala. Curr. Biol. 17, R868–R874.
Lee, S.P., Sung, I.-K., Kim, J.H., Lee, S.-Y., Park, H.S., Shim, C.S., 2015. The effect of emotional stress and depression on the prevalence of digestive diseases. Journal of neurogastroenterology and motility 21, 273.
Lee, Y.-A., Obora, T., Bondonny, L., Toniolo, A., Mivielle, J., Yamaguchi, Y., Kato, A., Takita, M., Goto, Y., 2018. The effects of housing density on social interactions and their correlations with serotonin in rodents and primates. Sci. Rep. 8, 3497.
Li, Y., Qin, J., Yan, J., Zhang, N., Xu, Y., Zhu, Y., Sheng, L., Zhu, X., Ju, S., 2019. Differences of physical vs. psychological stress: evidences from glucocorticoid receptor expression, hippocampal subfields injury, and behavioral abnormalities. Brain imaging and behavior 13, 1780–1788.
Licinio, J., Wong, M.L., 2002. Brain-derived neurotrophic factor (BDNF) in stress and affective disorders. Mol. Psychiatr. 7, 519-519.
Lieggi, C., Kalueff, A.V., Lawrence, C., Collymore, C., 2020. The influence of behavioral, social, and environmental factors on reproducibility and replicability in aquatic animal models. ILAR J.
Liu, J., Hu, P., Qi, X.R., Meng, F.T., Kalsbeek, A., Zhou, J.N., 2011. Acute restraint stress increases intrahypothalamic oestradiol concentrations in conjunction with increased hypothalamic oestrogen receptor β and aromatase mRNA expression in female rats. J. Neuroendocrinol. 23, 435–443.
Lukkes, J.L., Mokin, M.V., Scholl, J.L., Forster, G.L., 2009. Adult rats exposed to early-life social isolation exhibit increased anxiety and conditioned fear behavior, and altered hormonal stress responses. Horm. Behav. 55, 248–256.
Maeng, L.Y., Milad, M.R., 2015. Sex differences in anxiety disorders: interactions between fear, stress, and gonadal hormones. Horm. Behav. 76, 106–117.
Martinez, M., Calvo-Torrent, A., Pico-Alfonso, M.A., 1998. Social defeat and subordination as models of social stress in laboratory rodents: a review. Aggress. Behav.: Official Journal of the International Society for Research on Aggression 24, 241–256.
Mayo, L.M., Heilig, M., 2019. In the face of stress: interpreting individual differences in stress-induced facial expressions. Neurobiology of stress 10, 100166.
McCormick, C.M., Smith, C., Mathews, I.Z., 2008. Effects of chronic social stress in adolescence on anxiety and neuroendocrine response to mild stress in male and female rats. Behav. Brain Res. 187, 228–238.
McEwen, B.S., Bowles, N.P., Gray, J.D., Hill, M.N., Hunter, R.G., Karatsoreos, I.N., Nasca, C., 2015. Mechanisms of stress in the brain. Nat. Neurosci. 18, 1353–1363.
McEwen, B.S., Stellar, E., 1993. Stress and the individual: mechanisms leading to disease. Arch. Intern. Med. 153, 2093–2101.
McGonigle, P., 2014. Animal models of CNS disorders. Biochem. Pharmacol. 87, 140–149.
McHenry, J., Carrier, N., Hull, E., Kabbaj, M., 2014. Sex differences in anxiety and depression: role of testosterone. Front. Neuroendocrinol. 35, 42–57.
McLean, C.P., Asnaani, A., Litz, B.T., Hofmann, S.G., 2011. Gender differences in anxiety disorders: prevalence, course of illness, comorbidity and burden of illness. J. Psychiatr. Res. 45, 1027–1035.
Mervaala, E., Föhr, J., Könönen, M., Valkonen-Korhonen, M., Vainio, P., Partanen, K., Partanen, J., Tiihonen, J., Viinamäki, H., Karjalainen, A.K., 2000. Quantitative MRI of the hippocampus and amygdala in severe depression. Psychol. Med. 30, 117–125.
Miller, R., Kirschbaum, C., 2019. Cultures under stress: a cross-national meta-analysis of cortisol responses to the Trier Social Stress Test and their association with anxiety-related value orientations and internalizing mental disorders. Psychoneuroendocrinology 105, 147–154.
Nesan, D., Vijayan, M.M., 2016. Maternal cortisol mediates hypothalamus-pituitary-interrenal Axis development in zebrafish. Sci. Rep. 6, 22582.
Nikinmaa, M., 1992. Membrane transport and control of hemoglobin-oxygen affinity in nucleated erythrocytes. Physiol. Rev. 72, 301–321.
Novais, A., Monteiro, S., Roque, S., Correia-Neves, M., Sousa, N., 2017. How age, sex and genotype shape the stress response. Neurobiology of stress 6, 44–56.
Nussey, S., Whitehead, S., 2001. Chapter 4: the Adrenal Gland. In: Endocrinology: an Integrated Approach. BIOS Scientific Publishers, Oxford.
Oberlander, T.F., Weinberg, J., Papsdorf, M., Grunau, R., Misri, S., Devlin, A.M., 2008. Prenatal exposure to maternal depression, neonatal methylation of human glucocorticoid receptor gene (NR3C1) and infant cortisol stress responses. Epigenetics 3, 97–106.
Ogwang, S.P., 2008. Inspection of a Novel Object by Wild and Laboratory Zebrafish (Danio rerio H.) in the Presence and Absence of Alarm Substance.
Panula, P., Chen, Y.-C., Priyadarshini, M., Kudo, H., Semenova, S., Sundvik, M., Sallinen, V., 2010. The comparative neuroanatomy and neurochemistry of zebrafish CNS systems of relevance to human neuropsychiatric diseases. Neurobiol. Dis. 40, 46–57.
Parker, M.O., Brock, A.J., Walton, R.T., Brennan, C.H., 2013. The role of zebrafish (Danio rerio) in dissecting the genetics and neural circuits of executive function. Front. Neural Circ. 7, 63-63.
Parker, M.O., Millington, M.E., Combe, F.J., 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.
Patchev, V.K., Patchev, A.V., 2006. Experimental models of stress. Dialogues Clin. Neurosci. 8, 417.
Patten, S.B., Wang, J.L., Williams, J.V., Currie, S., Beck, C.A., Maxwell, C.J., El-Guebaly, N., 2006. Descriptive epidemiology of major depression in Canada. Can. J. Psychiatr. 51, 84–90.
Paull, G.C., Filby, A.L., Giddins, H.G., Coe, T.S., Hamilton, P.B., Tyler, C.R., 2010. Dominance hierarchies in zebrafish (Danio rerio) and their relationship with reproductive success. Zebrafish 7, 109–117.
Pippal, J.B., Cheung, C.M.I., Yao, Y.-Z., Brennan, F.E., Fuller, P.J., 2011. Characterization of the zebrafish (Danio rerio) mineralocorticoid receptor. Mol. Cell. Endocrinol. 332, 58–66.
Planellas, S.R., Jin, X., Damsgard, B., Begout, M.-L., Mackenzie, S., 2020. Analysis across Diverse Fish Species Highlights No Conserved Transcriptome Signature for Proactive Behaviour.
Plotsky, P.M., Meaney, M.J., 1993. Early, postnatal experience alters hypothalamic corticotropin-releasing factor (CRF) mRNA, median eminence CRF content and stress-induced release in adult rats. Mol. Brain Res. 18, 195–200.
Price, J.S., 2013. An evolutionary perspective on anxiety and anxiety disorders. New insights into anxiety disorders 3–20.
Pryce, C.R., Fuchs, E., 2017. Chronic psychosocial stressors in adulthood: studies in mice, rats and tree shrews. Neurobiology of Stress 6, 94–103.
Radahmadi, M., Alaei, H., Sharifi, M.R., Hosseini, N., 2015. Effects of different timing of stress on corticosterone, BDNF and memory in male rats. Physiol. Behav. 139, 459–467.
Raff, H., Sharma, S.T., Nieman, L.K., 2011. Physiological basis for the etiology, diagnosis, and treatment of adrenal disorders: cushing's syndrome, adrenal insufficiency, and congenital adrenal hyperplasia. Comp. Physiol. 4, 739–769.
Rambo, C.L., Mocelin, R., Marcon, M., Villanova, D., Koakoski, G., de Abreu, M.S., Oliveira, T.A., Barcellos, L.J.G., Piato, A.L., Bonan, C.D., 2017. Gender differences in aggression and cortisol levels in zebrafish subjected to unpredictable chronic stress. Physiol. Behav. 171, 50–54.
Ramsay, J.M., Feist, G.W., Varga, Z.M., Westerfield, M., Kent, M.L., Schreck, C.B., 2006. Whole-body cortisol is an indicator of crowding stress in adult zebrafish, Danio rerio. Aquaculture 258, 565–574.
Ramsay, J.M., Feist, G.W., Varga, Z.M., Westerfield, M., Kent, M.L., Schreck, C.B., 2009. Whole-body Cortisol Response of Zebrafish to Acute Net Handling Stress, vol. 297. Aquaculture, Amsterdam, Netherlands), pp. 157–162.
Randall, D.J., Ferry, S.F., 1992. 4 Catecholamines, Fish Physiology. Elsevier, pp. 255–300.
Razzoli, M., Carboni, L., Andreoli, M., Ballottari, A., Arban, R., 2011. Different susceptibility to social defeat stress of BalbC and C57BL6/J mice. Behav. Brain Res. 216, 100–108.
Reid, S.G., Perry, S.F., 1994. Storage and differential release of catecholamines in rainbow trout (Oncorhynchus mykiss) and American eel (Anguilla rostrata). Physiol. Zool. 67, 216–237.
Resnick, S.G., Bond, G.R., Mueser, K.T., 2003. Trauma and posttraumatic stress disorder in people with schizophrenia. J. Abnorm. Psychol. 112, 415.
Ressler, K.J., 2010. Amygdala activity, fear, and anxiety: modulation by stress. Biol. Psychiatr. 67, 1117–1119.
Reul, J., Kloet, E.R.D., 1985. Two receptor systems for corticosterone in rat brain: microdistribution and differential occupation. Endocrinology 117, 2505–2511.
Ridderinkhof, K.R., Ullsperger, M., Crone, E.A., Nieuwenhuis, S., 2004. The role of the medial frontal cortex in cognitive control. Science 306, 443–447.

Roebuck, M.M., Jones, C.T., Robinson, J.S., Mitchell, M.D., Thorburn, G.D., 1984. ACTH control of steroid secretion from adrenal cells of the developing rhesus monkey (Macaca mulatta). Acta Endocrinol. 105, 545–551.
Russell, G., Lightman, S., 2019. The human stress response. Nat. Rev. Endocrinol. 15, 525–534.
Russo, S.J., Nestler, E.J., 2013. The brain reward circuitry in mood disorders. Nat. Rev. Neurosci. 14, 609–625.
Sadoul, B., Geffroy, B., 2019. Measuring cortisol, the major stress hormone in fishes. J. Fish. Biol. 94, 540–555.
Sailaja, B.S., Cohen-Carmon, D., Zimmerman, G., Soreq, H., Meshorer, E., 2012. Stress-induced epigenetic transcriptional memory of acetylcholinesterase by HDAC4. Proc. Natl. Acad. Sci. Unit. States Am. 109, E3687–E3695.
Santini, Z.I., Jose, P.E., York Cornwell, E., Koyanagi, A., Nielsen, L., Hinrichsen, C., Meilstrup, C., Madsen, K.R., Koushede, V., 2020. Social disconnectedness, perceived isolation, and symptoms of depression and anxiety among older Americans (NSHAP): a longitudinal mediation analysis. The Lancet Public Health 5, e62–e70.
Schaaf, M.J., Champagne, D., van Laanen, I.H., van Wijk, D.C., Meijer, A.H., Meijer, O.C., Spaink, H.P., Richardson, M.K., 2008. Discovery of a functional glucocorticoid receptor beta-isoform in zebrafish. Endocrinology 149, 1591–1599.
Schioth, H.B., Chhajlani, V., Muceniece, R., Klusa, V., Wikberg, J.E., 1996. Major pharmacological distinction of the ACTH receptor from other melanocortin receptors. Life Sci. 59, 797–801.
Schreck, C.B., Tort, L., 2016. 1 - the Concept of Stress in Fish. In: Schreck, C.B., Tort, L., Farrell, A.P., Brauner, C.J. (Eds.), Fish Physiology. Academic Press, pp. 1–34.
Seale, J.V., Wood, S.A., Atkinson, H.C., Harbuz, M.S., Lightman, S.L., 2004. Gonadal steroid replacement reverses gonadectomy-induced changes in the corticosterone pulse profile and stress-induced hypothalamic-pituitary-adrenal axis activity of male and female rats. J. Neuroendocrinol. 16, 989–998.
Séguret, A., Collignon, B., Halloy, J., 2016. Strain differences in the collective behaviour of zebrafish (Danio rerio) in heterogeneous environment. Royal Society open science 3, 160451.
Shams, S., Chatterjee, D., Gerlai, R., 2015. Chronic social isolation affects thigmotaxis and whole-brain serotonin levels in adult zebrafish. Behav. Brain Res. 292, 283–287.
Shams, S., Khan, A., Gerlai, R., 2020. Early social deprivation does not affect cortisol response to acute and chronic stress in zebrafish. Stress 1–9.
Shams, S., Seguin, D., Facciol, A., Chatterjee, D., Gerlai, R., 2017. Effect of social isolation on anxiety-related behaviors, cortisol, and monoamines in adult zebrafish. Behav. Neurosci. 131, 492–504.
Skoluda, N., Strahler, J., Schlotz, W., Niederberger, L., Marques, S., Fischer, S., Thoma, M.V., Spoerri, C., Ehlert, U., Nater, U.M., 2015. Intra-individual psychological and physiological responses to acute laboratory stressors of different intensity. Psychoneuroendocrinology 51, 227–236.
Song, C., Berridge, K.C., Kalueff, A.V., 2016a. 'Stressing' rodent self-grooming for neuroscience research. Nat. Rev. Neurosci. 17, 591-591.
Song, C., Berridge, K.C., Kalueff, A.V., 2016b. 'Stressing'rodent self-grooming for neuroscience research. Nat. Rev. Neurosci. 17, 591-591.
Song, C., Liu, B.-P., Zhang, Y.-P., Peng, Z., Wang, J., Collier, A.D., Echevarria, D.J., Savelieva, K.V., Lawrence, R.F., Rex, C.S., Meshalkina, D.A., Kalueff, A.V., 2018. Modeling consequences of prolonged strong unpredictable stress in zebrafish: complex effects on behavior and physiology. Prog. Neuro Psychopharmacol. Biol. Psychiatr. 81, 384–394.
Sorge, R.E., Martin, L.J., Isbester, K.A., Sotocinal, S.G., Rosen, S., Tuttle, A.H., Wieskopf, J.S., Acland, E.L., Dokova, A., Kadoura, B., Leger, P., Mapplebeck, J.C., McPhail, M., Delaney, A., Wigerblad, G., Schumann, A.P., Quinn, T., Frasnelli, J., Svensson, C.I., Sternberg, W.F., Mogil, J.S., 2014. Olfactory exposure to males, including men, causes stress and related analgesia in rodents. Nat. Methods 11, 629–632.
Spagnoli, S., Lawrence, C., Kent, M.L., 2016. 13 - Stress in Fish as Model Organisms. In: Schreck, C.B., Tort, L., Farrell, A.P., Brauner, C.J. (Eds.), Fish Physiology. Academic Press, pp. 541–564.
Sperry, M.M., Yu, Y.-H., Welch, R.L., Granquist, E.J., Winkelstein, B.A., 2018. Grading facial expression is a sensitive means to detect grimace differences in orofacial pain in a rat model. Sci. Rep. 8, 1–10.
Stankiewicz, A.M., Swiergiel, A.H., Lisowski, P., 2013. Epigenetics of stress adaptations in the brain. Brain Res. Bull. 98, 76–92.
Steimer, T., Driscoll, P., 2005. Inter-individual vs line/strain differences in psychogenetically selected Roman High-(RHA) and Low-(RLA) Avoidance rats: neuroendocrine and behavioural aspects. Neurosci. Biobehav. Rev. 29, 99–112.
Steinman, M.Q., Trainor, B.C., 2017. Sex differences in the effects of social defeat on brain and behavior in the California mouse: insights from a monogamous rodent. Semin. Cell Dev. Biol. 61, 92–98.
Stewart, A.M., Braubach, O., Spitsbergen, J., Gerlai, R., Kalueff, A.V., 2014. Zebrafish models for translational neuroscience research: from tank to bedside. Trends Neurosci. 37, 264–278.
Stewart, A.M., Kaluyeva, A.A., Poudel, M.K., Nguyen, M., Song, C., Kalueff, A.V., 2015. Building zebrafish neurobehavioral phenomics: effects of common environmental factors on anxiety and locomotor activity. Zebrafish 12, 339–348.
Sullivan, R.M., Gratton, A., 1999. Lateralized effects of medial prefrontal cortex lesions on neuroendocrine and autonomic stress responses in rats. J. Neurosci. 19, 2834–2840.
Sumpter, J.P., Pottinger, T.G., Rand-Weaver, M., Campbell, P.M., 1994. The Wide-Ranging Effects of Stress on Fish. National Research Council of Canada, pp. 535–538.
Szklarczyk, K., Korostynski, M., Golda, S., Solecki, W., Przewlocki, R., 2012. Genotype-dependent consequences of traumatic stress in four inbred mouse strains. Gene Brain Behav.
Trainor, B.C., Takahashi, E.Y., Campi, K.L., Florez, S.A., Greenberg, G.D., Laman-Maharg, A., Laredo, S.A., Orr, V.N., Silva, A.L., Steinman, M.Q., 2013. Sex differences in stress-induced social withdrawal: independence from adult gonadal hormones and inhibition of female phenotype by corncob bedding. Horm. Behav. 63, 543–550.
Tran, S., Chatterjee, D., Gerlai, R., 2014. Acute net stressor increases whole-body cortisol levels without altering whole-brain monoamines in zebrafish. Behav. Neurosci. 128, 621–624.
Tran, S., Gerlai, R., 2013. Individual differences in activity levels in zebrafish (Danio rerio). Behav. Brain Res. 257, 224–229.
Tran, S., Gerlai, R., 2015. Thirty-second net stressor task in adult zebrafish. Bio-protocol 5, e1413.
Ulrich-Lai, Y.M., Herman, J.P., 2009. Neural regulation of endocrine and autonomic stress responses. Nat. Rev. Neurosci. 10, 397.
Usa, K., Singh, R.J., Netzel, B.C., Liu, Y., Raff, H., Liang, M., 2007. Renal interstitial corticosterone and 11-dehydrocorticosterone in conscious rats. Am. J. Physiol. Ren. Physiol. 293, F186–F192.
Valzelli, L., 1973. The "isolation syndrome" in mice. Psychopharmacologia 31, 305–320.
van den Bos, R., Mes, W., Galligani, P., Heil, A., Zethof, J., Flik, G., Gorissen, M., 2017a. Further characterisation of differences between TL and AB zebrafish (Danio rerio): gene expression, physiology and behaviour at day 5 of the larval stage. PloS One 12, e0175420.
van den Bos, R., Zethof, J., Flik, G., Gorissen, M., 2017b. Light regimes differentially affect baseline transcript abundance of stress-axis and (neuro) development-related genes in zebrafish (Danio rerio, Hamilton 1822) AB and TL larvae. Biology open 6, 1692–1697.
Van Der Knaap, L.J., Riese, H., Hudziak, J.J., Verbiest, M., Verhulst, F.C., Oldehinkel, A. J., Van Oort, F.V.A., 2014. Glucocorticoid receptor gene (NR3C1) methylation following stressful events between birth and adolescence. The TRAILS study. Transl. Psychiatry 4 e381-e381.
Vargas, J., Junco, M., Gomez, C., Lajud, N., 2016. Early life stress increases metabolic risk, HPA Axis reactivity, and depressive-like behavior when combined with postweaning social isolation in rats. PloS One 11 e0162665-e0162665.
Ver Hoeve, E.S., Kelly, G., Luz, S., Ghanshani, S., Bhatnagar, S., 2013. Short-term and long-term effects of repeated social defeat during adolescence or adulthood in female rats. Neuroscience 249, 63–73.
Vera-Chang, M.N., St-Jacques, A.D., Gagné, R., Martyniuk, C.J., Yauk, C.L., Moon, T.W., Trudeau, V.L., 2018. Transgenerational hypocortisolism and behavioral disruption are induced by the antidepressant fluoxetine in male zebrafish Danio rerio</em&gt. Proc. Natl. Acad. Sci. Unit. States Am., 201811695
Vermeirssen, E.L., Scott, A.P., 1996. Excretion of free and conjugated steroids in rainbow trout (Oncorhynchus mykiss): evidence for branchial excretion of the maturation-inducing steroid, 17,20 beta-dihydroxy-4-pregnen-3-one. Gen. Comp. Endocrinol. 101, 180–194.
Vignet, C., Bégout, M.-L., Péan, S., Lyphout, L., Leguay, D., Cousin, X., 2013. Systematic screening of behavioral responses in two zebrafish strains. Zebrafish 10, 365–375.
Volgin, A.D., Yakovlev, O.A., Demin, K.A., de Abreu, M.S., Alekseeva, P.A., Friend, A.J., Lakstygal, A.M., Amstislavskaya, T.G., Bao, W., Song, C., 2019. Zebrafish models for personalized psychiatry: insights from individual, strain and sex differences, and modeling gene x environment interactions. J. Neurosci. Res. 97, 402–413.
Wang, Y., Ge, W., 2004. Cloning of zebrafish ovarian P450c17 (CYP17, 17α-hydroxylase/17, 20-lyase) and characterization of its expression in gonadal and extra-gonadal tissues. Gen. Comp. Endocrinol. 135, 241–249.
Wendelaar Bonga, S.E., 1997a. The stress response in fish. Physiol. Rev. 77, 591–625.
Wendelaar Bonga, S.E., 1997b. The stress response in fish. Physiol. Rev. 77, 591–625.
Wilson, D.M., Errasti-Ibarrondo, B., Low, G., 2019. Where are we now in relation to determining the prevalence of ageism in this era of escalating population ageing? Ageing Res. Rev. 51, 78–84.
Wong, R.Y., French, J., Russ, J.B., 2019. Differences in stress reactivity between zebrafish with alternative stress coping styles. Royal Society open science 6, 181797-181797.
Wood, G.E., Shors, T.J., 1998. Stress facilitates classical conditioning in males, but impairs classical conditioning in females through activational effects of ovarian hormones. Proc. Natl. Acad. Sci. U.S.A. 95, 4066–4071.
Wullimann, M.F., Rupp, B., Reichert, H., 1996. Introduction: Neuroanatomy for a Neurogenetic Model System. In: Wullimann, M.F., Rupp, B., Reichert, H. (Eds.), Neuroanatomy of the Zebrafish Brain: A Topological Atlas. Birkhäuser Basel, Basel, pp. 1–5.
Yang, L., Wang, J., Wang, D., Hu, G., Liu, Z., Yan, D., Serikuly, N., Alpyshov, E.T., Demin, K.A., Strekalova, T., de Abreu, M.S., Song, C., Kalueff, A.V., 2020. Delayed behavioral and genomic responses to acute combined stress in zebrafish, potentially relevant to PTSD and other stress-related disorders: focus on neuroglia, neuroinflammation, apoptosis and epigenetic modulation. Behav. Brain Res. 389, 112644.
Zhang, L., Chen, C., Qi, J., 2020. Activation of HDAC4 and GR signaling contributes to stress-induced hyperalgesia in the medial prefrontal cortex of rats. Brain Res. 1747, 147051.
Zhou, C., Zhong, J., Zou, B., Fang, L., Chen, J., Deng, X., Zhang, L., Zhao, X., Qu, Z., Lei, Y., Lei, T., 2017. Meta-analyses of comparative efficacy of antidepressant medications on peripheral BDNF concentration in patients with depression. PloS One 12 e0172270-e0172270.