# The Effect of Maternal Separation on the Stress Response of *A. burtoni*

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A Thesis
Presented to
The Established Interdisciplinary Committee for Neuroscience
Reed College

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In Partial Fulfillment
of the Requirements for the Degree
Bachelor of Arts

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Marissa Breanne Borrego

May 2019

Approved for the Committee
(Neuroscience)

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Suzy C. P. Renn

# Acknowledgements

> Any situation in which some individuals prevent others from engaging in the process of inquiry is one of violence.
>
> *Paulo Freire*
> *Pedagogy of the Oppressed*

I have been so very privileged to have the experience of attending college and writing a thesis. I would like to thank:

◦ Suzy for pushing me to take the thesis process into my own hands and not giving up on me. Also to the rest of the Renn lab for helping me learn the ways of fish research.

◦ Paul for mentoring me throughout my undergraduate experience and giving me so many opportunities to learn.

◦ Larry for supporting me in my research and giving me so much encouragement and so many resources.

◦ Karen and Jonathan for taking me to libraries, parks, museums, concerts, and the like. Not bad for a couple of eloped, new wave-loving kids.

◦ Presence for letting me curl up in a ball on the floor, for encouraging me to challenge the systems I am a part of, for so much more.

◦ Pax, Pixie, and Noah for accompanying me on weird adventures through Eastern Oregon and through exploring my identity.

◦ James for inspiring me to study neuroscience and for giving me endless love and support.

◦ Matt for being a constant source of positivity and a great listener.

◦ Sonya for keeping up the puke & rally spirit while working in the library.

◦ Langston for ensuring that I made it out of this year alive and for supporting my curiosities in math, programming, communicative relationships, softness, pretentious Portland stereotypes, etc.

◦ Sarah, Sage, and Cody for never questioning why I was always in your house.

◦ Duncan for opening your arms after every time I ignored your advice and then regretted doing so. You are such a strong being.

◦ Cam for being a great friend, an absent roommate, an incredible scientist, and perhaps most importantly, a truly interesting person.

# Preface

> You don't have to choose between being scientific and being compassionate.
>
> Robert Sapolsky
> *Behave*

Science has a history as an oppressive institution. That being said, I think that science also has the ability to liberate individuals. We must strive to understand how the spaces we create impact one another and to interrogate the ways in which we judge people's ability to control their actions. I hope that at the least this thesis makes one think of how plastic we are to our day-to-day experiences.

# List of Abbreviations

| | |
|---|---|
| **11$\beta$-HSD2** | 11$\beta$-hydroxysteroid dehydrogenase type 2 |
| **ACTH** | Adrenocorticotropin hormone |
| **CRH** | Corticotropin-releasing hormone |
| **CPP** | Conditioned place preference |
| **$C_q$** | Cycle quantification |
| **GR** | Glucocorticoid receptor |
| **GRE** | Glucocorticoid response element |
| **HLG** | High licking & grooming |
| **HPA** | Hypothalamic-pituitary-adrenal |
| **LLG** | Low licking & grooming |
| **PCR** | Polymerase chain reaction |
| **PVN** | Pareventricular nucleus |
| **qPCR** | Quantitative polymerase chain reaction |
| **SQ** | Starting quantity |

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# Abstract

The ability of a developing organism to adjust to its early life environment is an important adaptation. That being said, when the adult environment does not match the early environment, these adjustments can be harmful. Exposure to early life stress is known to be correlated with a number of neuropathologies and developmental disorders in humans. Early life stress is able to reprogram the hypothalamic-pituitary-adrenal axis of organisms, leading to an alteration in the stress response. In mammals, poor maternal care is associated with an increase in circulating corticosteroids and anxiety-like behavior in stressful situations that persists throughout adulthood. This change in responsiveness to stressful situations is also accompanied by a decrease in inhibitory feedback of the hypothalamic-pituitary-adrenal axis, as measured by decreased glucocorticoid receptors. The present study aimed to model these mammalian studies in the mouthbrooding cichlid species *A. burtoni*. Mouthbrooding females were placed into one of two conditions: maternal care or maternal separation. In the maternal care condition, fry were allowed to stay with their mothers for the first two weeks post-fertilization. In the maternal separation condition, fry were removed from their mothers' buccal cavities shortly after fertilization. Stress-related behavior was measured through boldness and aggression assays while stress response was measured through glucocorticoid receptor expression. Fry separated from their mothers spent more time in the bottom of the novel tank compared to unseparated fry, suggesting an increase in boldness. There was no significant difference between conditions in body index, aggression, or glucocorticoid receptor expression; however, there was a positive correlation between GR1a and GR2 receptor expression as well as GR1b and GR2 receptor expression. Further research is needed in order to assess whether maternal separation in *A. burtoni* is comparable to low maternal care in mammals.

# Dedication

And in our hearts
How beautiful the flames that will
flare up in a ring

---

Chika Sigawa
"Mountain Range"

For Langston.

# Chapter 1

# Introduction

## 1.1 A Brief History of Nature *vs* Nurture

A defining feature of living organisms is that they are able to respond to stimuli in their environment. In other words, they behave. Each behavior requires a stimulus, or multiple stimuli, that triggers a chain reaction of internal responses, changing how an organism exists in its environment. In understanding why an animal responds to a stimulus in the way that it does, there are two places to start. One can look to the organism's genotype: was this behavior inherited genetically from its parents? Or one can look to the organism's upbringing: was this behavior learned in response to the environment? Traditionally, these two possibilities have been thought of as separate and exclusive, as in the phrase "nature *vs* nurture"; however, this notion of the two as separate influences has since changed.

The dichotomy of nature and nurture as we know it today has its unfortunate beginnings in the field of eugenics. The phrase was popularized by the father of eugenics, Francis Galton, in the late 19th century in an effort to understand if human "ability" was heritable. He defined nature as "all that a man brings with himself into the world" and nurture as "every influence from without that affects him after his birth" (Galton, 1874). While there was not yet a concept of DNA, both Darwin's theory of evolution and Mendel's inheritence experiments were in circulation. The

interest in nature *vs* nurture remained within developmental psychology until late in the 20th century when behavioral and developmental neurosciences were popularized.

In the early and mid 20th century, the fields of animal behavior and genetics were being revolutionized in ways that would ultimately contribute to the debate of nature and nurture (Krubitzer and Kahn, 2003). In the 1930's a pioneering behavioral scientist by the name of Nikolaas Tinbergen began studying behaviors holistically, as a product of individual experience and evolution. He was interested in creating a scientifically rigorous way by which to observe and comment on behavior. What emerged was the modern field of ethology and a set of four categories to study a behavior through: causation (mechanism), survival value (adaptation), ontogeny, and evolution (Tinbergen, 1963). Tinbergen's four questions were important in examining a single behavior as a product of an individual's experiences and that individual's lineage. That being said, there was still not that much known about molecular biology and its role in behavior.

Abstract concepts of DNA and RNA as a heritable molecule had been proposed by the early 20th century in response to heritability studies (Koltzoff, 1934; Hershey and Chase, 1952), but it wasn't until Francis Crick and James Watson published a study in 1953 on the structure of DNA (notably, the study relied heavily on prior work by Rosalind Franklin) that the field of modern genetics really began (Watson and Crick, 1953). Using information about base pairs and amino acids published by other labs at the time, Crick proposed the central dogma of genetics in 1958 (Crick, 1958). This crucial concept states that DNA is translated into RNA, which is then transcribed into amino acids that are linked together to form proteins (Figure 1.1).

The last big step in getting to our current concept of nature and nurture was the popularization of epigenetics. Epigenetics in short refers to the factors that change the ability of DNA to be transcribed, contributing to changes in gene expression. Much of modern behavioral sciences is aimed at understanding how the environment

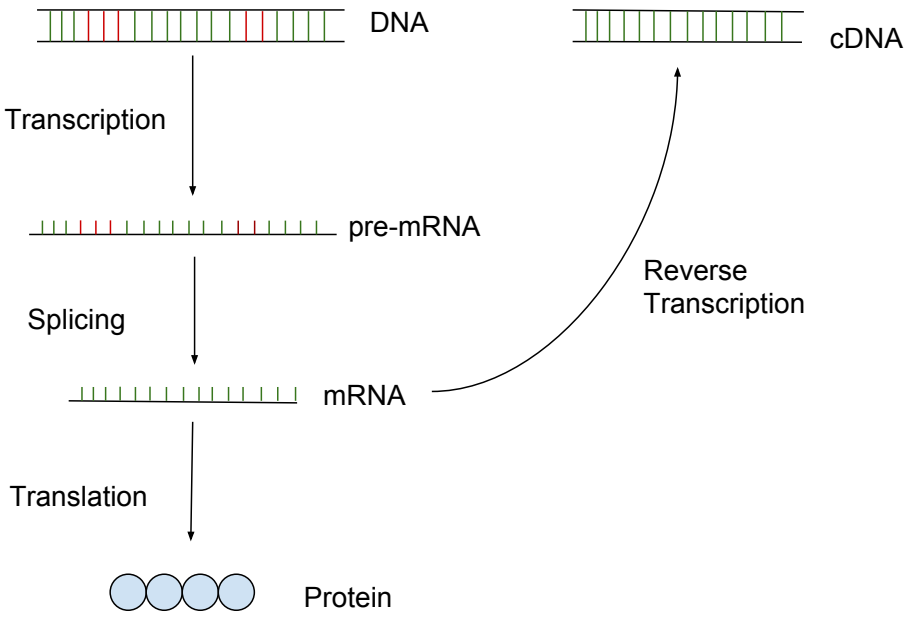


Figure 1.1: The central dogma of molecular biology including reverse transcription.
The central dogma of molecular biology explains how DNA informs protein structure. DNA is transcribed into pre-mRNA. The introns (red), or non-coding regions, of the pre-mRNA are then spliced out, leaving only the exons (green). The spliced mRNA is then translated into a sequence of amino acids that together form a protein. Reverse transcription is the process of making mRNA into a double stranded nucleic acid known as cDNA. Unlike DNA, cDNA does not contain the sequences of introns.

influences an organism's epigenome.

Because we now understand gene expression is often altered by the environment, our notion of nature *vs* nurture becomes rather arbitrary. Behaviors can instead be thought of as an interaction of nature *and* nurture (Sasaki and Kim, 2017; Meaney, 2006). Rather than understanding the ratio of environmental to genetic influence on a behavior, we can instead examine how certain genotypes make an organism more vulnerable to environmental influences or how the environment influences the ways in which the genome is utilized. The following research examines how early-life environment can influence the transcription of glucocorticoid receptor genes and with that influence stress-related behavior.

## 1.2 The Hypothalamic-Pituitary-Adrenal Axis

### 1.2.1 Activation of the HPA Axis

If you have made it this far in life, you have at some point felt *stressed*. Stress can be defined as the body's *response to* and *recovery from* a threat that disrupts homeostatis (van Bodegom et al., 2017). An important aspect of the stress response is the production and mobilization of energy. This is made possible through the hypothalamic-pituitary-adrenal (HPA) axis, which functions to produce glucocorticoids (Figure 1.2). As the name suggests, glucocorticoids play a role in the metabolism of glucose, the body's main source of energy.

The activation of the HPA axis begins with stimulation of the hypothalamus by other brain areas. In the presence of an immediate stressor, brain regions associated with maintaining homeostasis trigger the axis. Take for example the response to a painful stimulus. Pain is sensed by nociceptors in the peripheral nervous system and cause afferent signaling to norepinephrinergic neurons in the hind brain. These hindbrain neurons can in turn stimulate the hypothalamic neurons involved in the

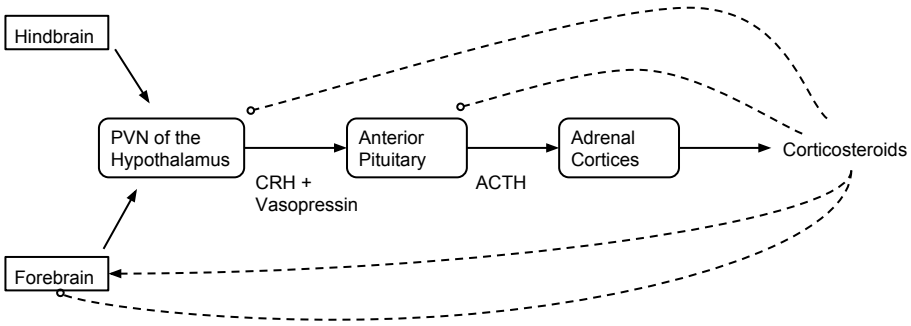


Figure 1.2: Signaling cascade of the HPA axis.
As a response to stress, forebrain or hindbrain projections to the hypothalamus can begin the HPA axis signalling cascade. The paraventricular nucleus (PVN) of the hypothalamus secretes corticotropin-releasing hormone (CRH) and vasopressin into the anterior pituitary. This causes the anterior pituitary to release adrenocorticotropin hormone (ACTH) into the bloodstream. ACTH reaches the adrenal cortices of the adrenal glands, leading to the production of steroid hormones including corticosteroids. While corticosteroids have many targets and regulatory effects, they can also have positive feedback effects (dashed arrowhead) and negative feedback effects (dashed open circle) for the HPA axis itself.

HPA axis. It is also possible to activate the HPA axis as an anticipatory response. If an animal has been conditioned to associate a given smell with a predator, then in the presence of that smell alone the animal may trigger the HPA axis in anticipation of the danger. This requires polysynaptic signaling from limbic structures involved in learning and fear such as the hippocampus (homologous to telencephalic pallium in teleosts) and amygdala (homologous to the medial pallium in teleots) (Salas et al., 2006). The hippocampus excites the axis through glutamatergic interneurons, whereas it is hypothesized that much of the excitatory amygdalar signaling works through disinhibition. In both the immediate and anticipated cases, the activation of neurons within the hypothalamus leads to a stereotyped cascade of signaling.

The hypothalamus is a region of the midbrain known for its role in maintaining allostasis through its involvement in stress, appetite, circadian rhythms, and sexual behavior. In response to a stressor, the paraventricular nucleus (PVN) of the hy-

pothalamus secretes corticotropin-releasing hormone (CRH) and vasopressin, which bind to receptors in the pituitary gland. The pituitary gland is directly ventral to the hypothalamus and is a main regulator of hormone release. The binding of CRH to $CRF_1$ receptors in the anterior pituitary leads to the secretion of adrenocorticotropin hormone (ACTH). This excitatory interaction can be potentiated by vasopressin, though vasopressin alone is not enough to produce an effect. ACTH enters the blood stream and travels to the adrenal cortices, which are the dorsal regions of the adrenal glands. In teleosts, the interrenal cells are homologous to the dorsal region as there is not a clear division between their kidneys and their adrenal glands (Pijanowski et al., 2015). ACTH binds to melanocortin 2 receptors, which increases the synthesis of cholesterol. Cholesterol is then transported to the outer mitochondrial matrix where the steroidogenic pathway begins. A major end product of this pathway and thus of the HPA axis is corticosteroids.

### 1.2.2 Glucocorticoid Receptors

Corticosteroids are steroid hormones that can bind to glucocorticoid receptors (GRs) and mineralocorticoid receptors. The term glucocorticoid refers to corticosteroids that are able to bind to GRs. After being released by the adrenal glands, glucocorticoids travel through the blood stream, pass through the blood-brain-barrier, and freely diffuse into the cytoplasm of neurons. Unbound GRs reside in the cytoplasm as part of a larger protein complex. When a GR is bound to by a glucocortiocoid it goes through a conformational change and sheds the protein complex. It is then transported to the nucleus where it dimerizes with another GR. The homodimer can then interact with other proteins, ultimately leading to the binding of the complex to a glucocorticoid response element (GRE) on the genome. These GREs are often found in the promotor region of their target genes, though sometimes they are distant from the target gene. The GRs can then recruit transcription factors that suppress or

enhance transcription of the target gene (Busada and Cidlowski, 2017; Herman et al., 2005) (Figure 1.3). The change in gene transcription by GRs can in turn change appetitive behavior, immune response, development, learning and memory, and other major behaviors (Busada and Cidlowski, 2017).

Interestingly, GRs can also localize to the mitochondria, where they can alter transcriptional elements of mitochondrial DNA. Due to mitochondria's role in steroid and energy production (Lapp et al., 2019), this finding suggests an important long-term regulatory role of glucocorticoids. Activated GRs can also have nongenomic consequences such as kinase activation, though these pathways are not well understood (Samarasinghe et al., 2011).

In mammals, there are eight known transcriptional isoforms of the GR gene (Saif et al., 2015) and thirteen different post-translational modification sites of the GR protein (Oakley and Cidlowski, 2013). These differences in protein structure alter the cellular function of the GR subtypes (Lu et al., 2007). A genome duplication event happened in the evolution of teleosts, causing them to have two GR paralogues: GR1 and GR2 (Glasauer and Neuhauss, 2014). The genetic sequences are highly similar to each other as well as to the GR genes of other species (Greenwood et al., 2003). Both GR1 and GR2 are expressed in corticosteroid responsive brain regions, suggesting that they both maintain signaling functionality.

### 1.2.3 Regulation of the HPA Axis

Activation of the HPA axis leads to situationally different levels and duration of glucocorticoid release. Inflammatory stressors often lead to prolonged stress responses, as the injury requires sustained energy to repair. Psychological stressors, in contrast, tend to lead to acute responses because there is no tissue repair or immune response required (Herman et al., 2016). Because the stress response is energy intensive, it is important that an organism responds appropriately to threatening situations.

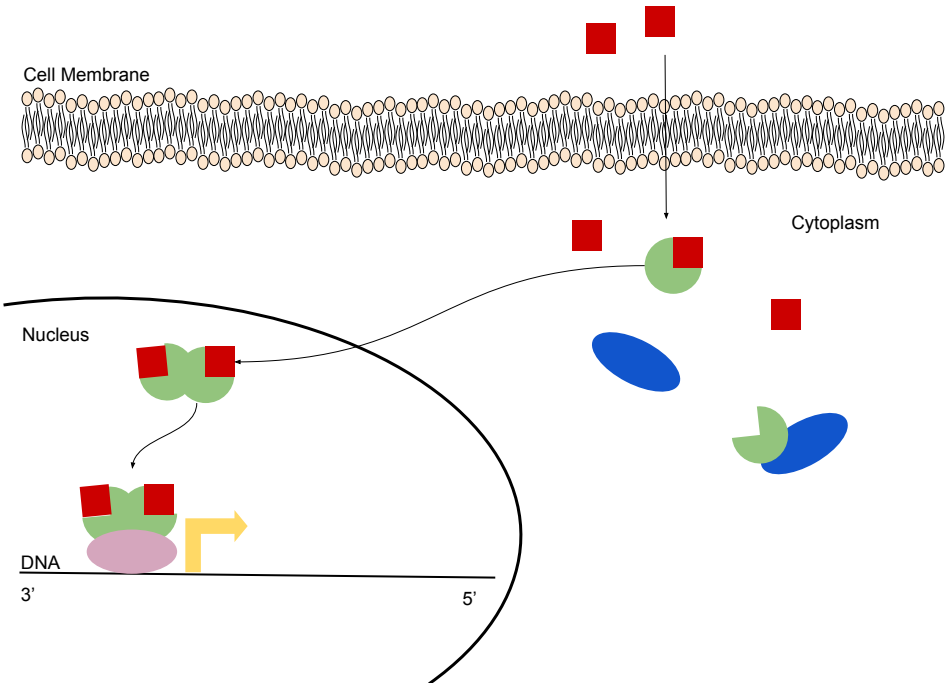


Figure 1.3: Glucocorticoid receptor mechanism of action.
Unbound glucocorticoid receptors (green) reside in the cytoplasm of cells as a part of a larger protein complex (blue). Corticosteroids (red) can freely diffuse through the cell membrane and bind to glucocorticoid receptors. Glucocorticoid receptors then undergo a conformational change, shedding the protein complex, and move into the nucleus. There they form homodimers and bind to glucocorticoid response elements (pink) on the genome. These elements are downstream of promotor regions (yellow) and can alter the transcription of nearby genes.

The HPA axis includes negative feedback loops that enact tight regulation. GR's play an inhibitory role in the activation of the HPA axis. They are abundantly expressed within the PVN. Upon activation, they cause endocannabinoid synthesis and release that are able to inhibit glucocorticoid receptors that target CRH neurons. Long term exposure to corticosteroids has also been shown to reduce pituitary ACTH release (Keller-Wood, 2015). In addition to regulation within the axis, GRs in the hippocampus and prefrontal cortex are able to inhibit HPA axis activity via GABAergic interneurons (van Bodegom et al., 2017).

The HPA axis has the ability to adjust to chronic stress. There is an important distinction to be made by the body between long-term stressors that continuously pose a threat to an organism and long-term stressors that don't actually pose a threat to

an organism. Take for example two deer that live in environments coinhabited by humans. The first lives in an area that is frequented by hunters. This deer has to induce a full stress response every time it encounters a human, else the animal will quickly be killed. Now take for example a deer that lives in a zoo. It would surely be a waste of this deer's energy if it were to enter a stressed state every time it encountered a human. While it is adaptive for the former deer to develop a heightened responsiveness to humans, it is adaptive for the latter deer to become desensitized to humans.

A long-term change to the physiology of the HPA axis can occur via epigenetic modification. In other words, the genes encoding proteins necessary for the HPA axis can be made more or less likely to be transcribed as a result of chemical changes to structural elements of the DNA. Epigenetic changes are heritable from parent to daughter cell even though they do not alter the actual DNA sequence, making them an important aspect of early development when cells are rapidly proliferating.

## 1.3 Stress and Development

### 1.3.1 Protection Against Early Life Stress

The fact that chronic stress is often unhealthy is quite intuitive. When an organism is forced to expend energy on immediate survival, it must forego less pressing, but very important processes like eating, sleeping, reproducing, and learning. Teleosts and mammals share a highly-conserved protection mechanism against early-life stress. In both cases, mothers secrete 11$\beta$-hydroxysteroid dehydrogenase type 2 (11$\beta$-HSD2) into the prenatal environment. This hormone rapidly deactivates corticosteroids, effectively inhibiting the stress response of embryos (van Bodegom et al., 2017; Faught et al., 2016). As newborns, there is a stress hyporesponsiveness period characterized by a decrease in circulating ACTH and corticosteroids, as well as an overall decrease

in responsiveness to stressors (van Bodegom et al., 2017; Barry et al., 1995).

Importantly, both of these defenses can be altered by a highly stressful environment. Repeated maternal exposure to stress decreases 11$\beta$-HSD2, increasing prenatal corticosteroid exposure. Maternal separation is associated with a shortened stress hyporesponsiveness period in mammals (no similar study has been published in fish). These findings suggest that the stress response is plastic to early life experience.

The match/mismatch hypothesis argues that this plasticity to the early life environment will be adaptive for the organism if the adult environment matches, but will be maladaptive for the organism if the adult environment is different (Gluckman et al., 2007). Take for example fear learning in rats exposed to early-life stress. While rats exposed to stress early in life had impaired learning compared to unstressed rats, they had enhanced learning when treated with corticosterone. Additionally, these stressed rats learned to associate foot shocks with unconditioned stimuli quicker than unstressed rats, indicative of their adaptation to stressful situations (Champagne et al., 2008). While these changes in behavior are helpful in a high-stress environment, they are harmful in the low-stress environment (Figure 1.4). Further, there are a number of negative developmental consequences that result from glucocortioid exposure.

### 1.3.2 The Effects of Prenatal Stress on Development

Glucocorticoid receptors play an important role in fetal development. While insufficient levels of glucocorticoids are sometimes fatal, causing undeveloped organs, excess circulating glucocorticoids can cause potentially maladaptive developmental reprogramming (Busada and Cidlowski, 2017). The offspring of pregnant mice treated with synthetic glucocorticoids have delayed maturation of neurons and glia as well as delayed vascularization of the brain (Gravanis and Mellon, 2011). Further, prenatal stress exposure is correlated with decreased dendritic spine density in the cingulate

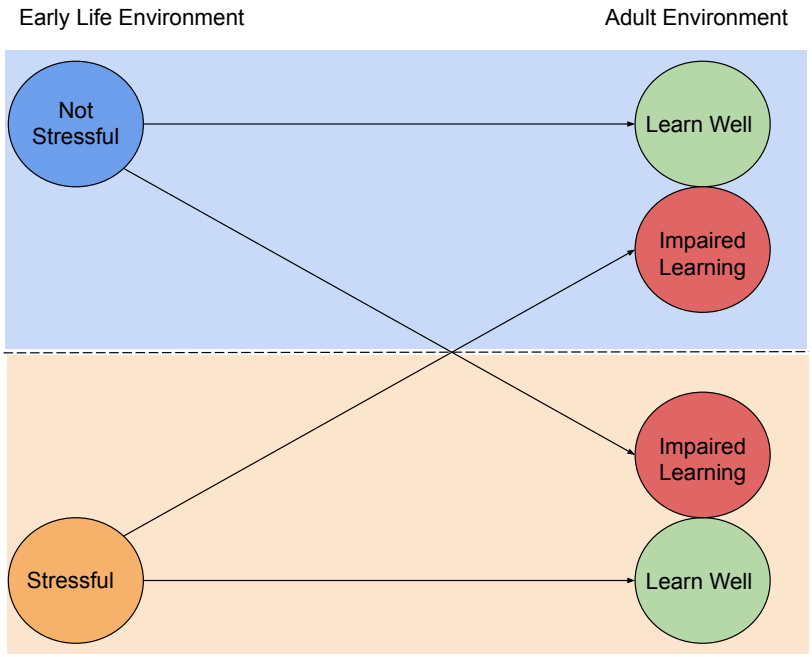


Figure 1.4: The Match/Mismatch Hypothesis
The match/mismatch hypothesis states that plasticity to early life environment is typically adaptive when the adult environment matches and maladaptive when the adult enviornment is mismatched. Rats that received low maternal care as pups had impaired learning and memory in non-stressful conditions compared to their high maternal care counterparts. This effect was reversed when learning and memory were tested under stressful conditions.

gyrus and orbitofrontal cortex (Murmu et al., 2006). These data suggest that prenatal stress alters the physiology and circuitry of the developing brain.

The ability of offspring to learn and form memories is altered by prenatal stress exposure. Rats have impaired spatial memory in the Y-maze and working memory in the radial arm maze when they were exposed to prenatal stress (Vallée et al., 1999). Rats also display a corresponding decrease in CAMKII and CREB mRNA expression in the hippocampus, a brain region heavily associated with learning and memory, under these conditions (Sun et al., 2017).

Animals exposed to prenatal stress are also more susceptible to addictive behavior,

as measured by conditioned place preference (CPP). In this paradigm, animals are conditioned to associate a drug with a given environment and then their preference for that environment over a neutral environment is measured in the absense of the drug. Rats with mothers exposed to stress have increased nicotine CPP as well as increased dopamine $D_2$ receptor gene expression in nucleus accumbens, a brain region associated with reward and thus addiction (Said et al., 2015). Prenatal stress has also been shown to increase CPP in response to benzodiazepines (Lakehayli et al., 2015), cocaine (Pastor et al., 2018), and morphine (Vey et al., 2016) just to name a few. This implies that changes in stress circuitry impacts other complex neural systems as well. In addition to addictive behavior, prenatal stress is a predictor of psychiatric disease in adults. Rodents exposed to prenatal stress show increased anxiety, depressive, and schizophrenic-like behavior compared to offspring of non-stressed dams (Weinstock, 2017). Taken together, these findings have major implications for understanding underlying mechanisms in neuropathologies.

### 1.3.3 Maternal Care and Stress in Rats

Stress in the postnatal environment can also be influential to an organism's development. The neuroscientist Michael Meaney has done years of groundbreaking work on how maternal care alters the stress response in rats. Rat mothers exhibit consistent differences in the time spent licking and grooming their young during their first week of life (Meaney et al., 1996). This difference takes place during a critical period of the rats' neural development. As a result, pups reared by high licking and grooming (HLG) mothers and low licking and grooming (LLG) mothers have distinct phenotypes and gene expression profiles (Weaver et al., 2004). Meaney cross-fostered pups from HLG and LLG mothers. As a result, pups born to LLG dams, but reared by HLG dams had a similar phenotype to those born to and reared by HLG dams (Francis et al., 1999). This indicates that the mother's behavior is largely responsible

for differences in the pups phenotypes and gene expression.

Meaney's lab examined how circulating stress hormones differed in pups reared by HLG and LLG mothers (Liu et al., 2000). HLG pups had reduced circulating levels of ACTH and corticosterone in response to restraint stress. Additionally, HLG pups appeared to have enhanced regulatory feedback in stressful situations, as they suppressed ACTH to a greater extent after being pre-treated with corticosterone (the murine equivalent of cortisol). HLG pups also developed higher GR expression in the hippocampus as adults, a brain region associated with HPA-axis inhibition. These molecular differences are also associated with distinct behavioral phenotypes between the two groups (Caldji et al., 1998). Rats reared by HLG dams exhibited more exploratory behavior, as measured by an open field paradigm, compared to those reared by LLG dams. Additionally, LLG pups exhibited a longer latency to start eating when placed in a novel environment compared to HLG pups. These findings indicated that maternal care can influence offspring's responses to stress as adults.

In 2004, Meaney's lab published a paper on the epigenetics of the above discoveries (Weaver et al., 2004). The lab found that the epigenetic state of the GR promoter gene was altered by maternal licking and grooming. This difference in methylation state was contingent on the rearing, not the biological, mother. GR receptor gene methylation was decreased and acetylation increased in HLG rats, consistent with earlier studies.

Taken together, the work of Meaney's lab demonstrates that rats reared by LLG dams have a hypersensitive stress response, characterized by increased circulating stress hormones, decreased hippocampal GR receptors, and decreased exploratory behavior. Mothers that are stressed decrease the amount of licking and grooming of their pups, suggesting that maternal care is indicative of environment (Zhang and Meaney, 2010). These findings support the match/mismatch hypothesis whereby stressful offsping conditions, like low maternal care, heighten the HPA-axis mediated

stress response to better match a stressful environment (Meaney et al., 1996; Liu et al., 2000).

Table 1.1: Summary of Meaney's work comparing high licking and grooming and low licking and grooming pup phenotypes.

| **Phenotype** | **Pups Reared by HGL Dams** | **Pups Reared by LLG Dams** |
|---|---|---|
| Circulating stress hormones | Low | High |
| Habituation to Corticosterone | High | Low |
| Hippocampal GR expression | High | Low |
| Anxiety-like behavior | Low | High |
| GR gene methylation | Low | High |
| GR gene acetylation | High | Low |

The work of Meaney has been incredibley impactful in our understanding of how parental care can shape the neuroendicrinology of offspring. Still, there exist many open questions about maternal care's impact on offspring including gene involvement, epigenetic states, and neural circuitry related to early life experience (Bolton et al., 2019; Lesuis et al., 2019; Bayerl and Bosch, 2019; Jenkins et al., 2018; Bolton et al., 2017). Currently, much of this work is being conducted in rodents. While this research is tremendously impactful due to the homology between rodents and humans, murine experiments are costly and slow, given that rodents require low-density housing and can take up to nine months to reach adulthood (Sengupta, 2013). In addition to the problems in efficiency of rodent research, the strains of mice and rats used in research have been selectively bred for generations and are far from their wild type ancestors (Perlman, 2016). The use of fish models in biomedical research have been growing in popularity (Harris et al., 2014; Cech and Zon, 2011). Fish are much less expensive and quicker to grow than rodent models, allowing for high throughput research. Additionally, some species of fish, like African cichlids come from relatively recently caught wildstock, allowing for natural genetic and behavior variation that better represents that of humans (Maruska et al., 2019; Renn et al., 2009).

### 1.3.4 Stress in Cichlids

While there doesn't exist much research on fish models of maternal separation, Barbara Taborsky has examined how early social environment influences fish stress response. Most of Taborsky's work is with *Neolamprologus pulcher*, a highly social cichlid species that lives in family units and collectively raises offspring. Immature fish help to keep eggs clean and well-oxygenated while adults defend the eggs against predators and conspecifics (Arnold and Taborsky, 2010).

Much of Taborsky's work has focused on how early life social experience affects social behavior and stress response in adults. Fish were divided into three groups: those raised with adults and immature helpers, those raised with just helpers, and those raised with neither helpers nor adults. In the following studies, fry raised in the presence of just helpers and fry raised in the presence of helpers and adults had the same trends. Taborsky found that *N. pulcher* fry raised in the absence of adults and helpers had decreased social competency, showing energetically costly levels of aggression in territory disputes (Arnold and Taborsky, 2010). Fish raised with adults had decreased whole-brain GR1 expression and CRH compared to those raised in the presence of adults or helpers (Taborsky et al., 2012).

A follow-up study in *N. pulcher* examining specific regions of the brain showed that fry raised in the presence of adults and helpers had increased in GR1 mRNA expression in the telencephalon (Nyman et al., 2018). *N. pulcher* fry raised in the absence of adults and helpers displayed more neophobia in behavioral tests, which is indicative of higher stress in new environments (Bannier et al., 2017). While *N. pulcher* is a great example of how early life social environment can influence the stress response, they do not model maternal care. Another species of cichlid, *Astatotilapia burtoni*, however, display maternal care behaviors and may be able to better mimick mammalian models.

Table 1.2: Summary of Taborsky's work comparing *N. pulcher* fry raised in the presence and absence of adults and adolescents.

| **Phenotype** | **Fry Raised with Older Fish** | **Fry Raised without Older Fish** |
|---|---|---|
| Social competency | High | Low |
| Circulating CRH | Low | High |
| Telencephalic GR1 expression | High | Low |
| Whole-brain GR1 expression | Low | High |
| Anxiety-like behavior | Low | High |

### 1.3.5 *Astatotilapia burtoni* as a Model Organism

*A. burtoni*, also referred to as *Haplochromis burtoni*, is a highly social cichlid species found in Lake Tanginyaka. Females take part in a offspring care strategy known as mouthbrooding. The female lays eggs and immediately picks them up, storing them in her buccal cavity. Shortly after this, the males fertilize the eggs. The mother keeps the offspring in her mouth for about two weeks as the eggs develop into fry. After the initial release, fry remain close to their mother and return to their mother's mouth in the presence of danger (Renn et al., 2009). Brooding mothers voluntarily starve themselves; however, in stressful situations they will eat their offspring. Mouthbrooding helps to protect the developing fry from predators and conspecifics, potentially reducing their exposure to stressful experiences (Renn et al., 2009).

The species has been used as a model organism in neuroendicrinology research due to its extremely plastic dominance phenotypes. There exists two distinct dominance phenotypes in males: those with territory that are reproductively active and those without territory that are reproductively suppressed (Fernald, 1977). Males with territory are dominant and have bright blue or yellow body coloration with a thick black stripe that passes over their eyes (Border et al., 2019). They have vertical black stripes along their body, a black spot on their gill cover, and a red splotch just caudal to that. Non-territorial males are subordinate and resemble females, with camouflage coloration (Figure 1.5).

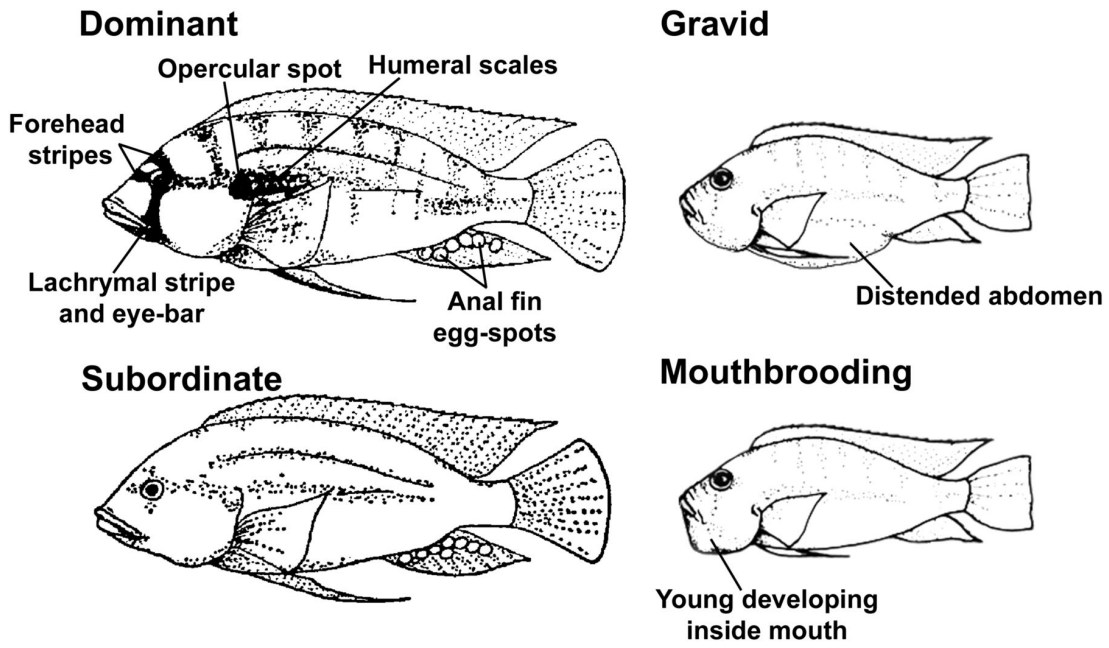


Figure 1.5: *A. burtoni* phenotypes (Fernald and Maruska, 2012)
*A. burtoni* have distinct social phenotypes. Dominant males (upper left) come in yellow and blue variations. They have a distinct black eye-bar, vertical black body stripes, and anal fin spots. Subordinate males (bottom left) are dull in coloration, similar to females.Reproductively active (gravid) females (right) lay their eggs and then carry the developing young in their buccal cavity for approximately 14 days.

The difference in dominance is also correlated with a difference in stress and hormonal regulation (Renn et al., 2008). Dominant males have increased testosterone and gonad size, while subordinate males have increased levels of cortisol and experience faster growth (Francis et al., 1993; Renn et al., 2008; Fox et al., 1997). Males are able two switch between these phenotypes throughout their lives in response to changes in their social interactions. Female *A. burtoni* also exhibit social dominance, though unlike the males, both dominant and subordinate females are reproductively active (Renn et al., 2012). Because of their known hormonal regulation, social plasticity, and mouthbrooding behavior, *A. burtoni* may be a good model organism for the effects of differing levels of maternal care in a fish species.

### 1.3.6 Current Investigation

The work of Barbara Taborsky has demonstrated that social fish species are plastic to their early life experience, showing changes in behavior and stress hormone expression as a result of social environment. Taborsky's work, however, is focused on the effect that social environment has on social behavior. There is little known about how maternal separation affects mouthbrooding fish. It is unknown to what extent mouthbrooding influences the neurophysiological development of fry. By comparing the effects of this offspring care strategy to what is known in mammals, we can better understand the evolution of neuronal plasticity in response to early life experience, especially as it relates to parental care. If the effects of maternal separation in teleost mimick those of mammals, they may be a good model in which to continue examining the underlying mechanisms behind the plethera of problems associated with early-life stress.

A recent thesis by Destine Krenik examined the potential of *A. burtoni* as a model organism for maternal separation studies through measuring behavior and neural GR expression (Krenik, 2018). Offspring were either reared with their mothers or were separated as eggs and raised without any adults. The thesis examined anxiety-like behavior and aggression in both conditions, but did not find any significant treatment-based differences. The brains of the fish were extracted and divided into forebrain, midbrain, and hindbrain for GR mRNA analysis. Krenik found significantly lower GR mRNA expression in the hindbrain of fry separated from mothers.

The following research is conceptually based on this thesis and continues to uncover the potential of *A. burtoni* as a model organism for maternal care studies; however, there were three major methodological changes made. The first is that the paradigm used to measure anxiety-like behavior in this thesis takes places in a more naturalistic tank to encourage some exploratory behavior. The second change is that this thesis will examine whole-brain GR mRNA expression rather than section the

brain into three regions. Lastly, the current research uses three different GR primers, as opposed to Krenik's use of a single primer, in order to quantify more splice variants. The rationale for these changes is to collect different data for the same overarching question in order to build a better understanding as to how maternal separation alters GRs.

I hypothesized that fish separated from their mothers would exhibit more anxiety like behavior and more aggression compared to those brooded by their mothers. This heightened stress response would be accompanied by a decrease in GR1a, GR1b, and GR2 receptor expression.

# Chapter 2

# Methods

## 2.1 The Fish

Table 2.1: Brood information

| Brood ID | Condition | Number of Fry |
|---|---|---|
| 0-0 | Unseparated | 1 |
| Z-1-3 | Separated | 2 |
| Z-1-7 | Unseparated | 3 |
| Z-1-9 | Unseparated | 3 |
| Z-2-1 | Unseparated | 2 |
| Z-2-4 | Separated | 3 |
| Z-2-9 | Separated | 1 |
| Z-3-1 | Separated | 3 |
| **Total** | **Unseparated = 4 broods**<br>**Separated = 4 broods** | **Unseparated = 9 fry**<br>**Separated = 9 fry** |

The parental generation of the focal juveniles originated from a wild-caught stock of *A. burtoni* collected in 2005 from Lake Tanganyika in East Africa (Renn et al., 2009). Social groups containing males and females of the same generation were kept in 30 gallon aquaria at a temperature of 28°C and a pH of 8.5. Each aquarium's bottom was covered in gravel, and terra cotta pot pieces were placed in the tank to act as shelters and territory markers. Once a female fish began mouthbrooding, she was removed from the aquarium and randomly placed into one of two experimental

conditions.

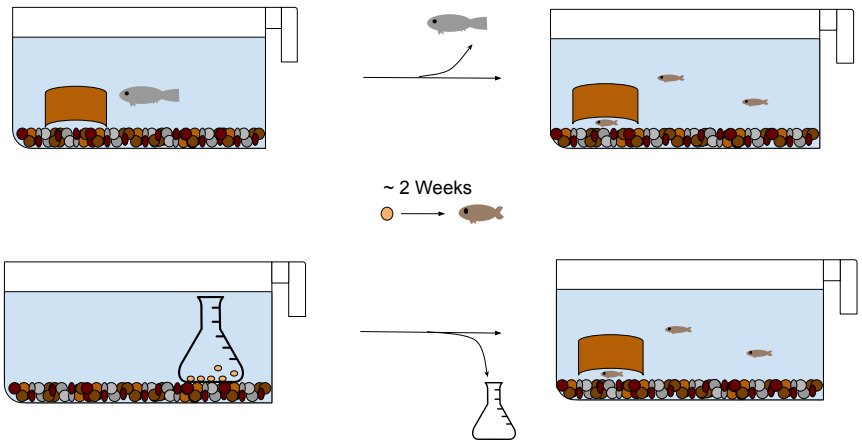


Figure 2.1: Experimental conditions.
Mouthbrooding fish were selected to be in either of two experimental groups. In the first condition (top) mothers were transferred to individual tanks containing gravel and a terra cotta piece. After about two weeks, when fry were able to leave their mothers' mouths, the mothers were moved back into their home aquaria. In the second condition (bottom), eggs were removed from the buccal cavity and placed in a flask within an individual tank. After about two weeks the fry were able to freely swim and the flask was removed.

In the unseparated condition, mothers were removed from their home tank, weighed, and measured. They were then placed individually in small tanks containing gravel and a piece of terra cotta pot. Mothers continued to brood their young until the fry were old enough to regularly leave their mother's mouth (approximately 2 weeks post-fertilization), at which point the mother was removed from the tank to prevent her from eating the fry (Figure 2.1).

In the separated condition, mothers were weighed and measured and then the eggs were removed from their mouths by gently pulling down the bottom jaw. The eggs were then placed in a 250 mL flask within an new tank containing gravel and circulating water. Once the eggs developed into freely moving fry (approximately 2 weeks post-fertilization), they were able to leave the flask and swim around the tank. At this point the flask was removed from the tank and a piece of terra cotta was added.


Figure 2.2: Timeline of experiment.
Two to three days after fertilization of eggs occurred, the broods were placed into one of two conditions: maternal separation or no maternal separation. After approximately two weeks, the fry were old enough to freely swim around their tanks. At this point, depending on the condition, either the mother or the flask was removed from the tank. The fry were allowed to age for about 130 days, at which point they were exposed to the boldness and aggression assays. Immediately after the behavioral testing, the fish were decapitated and their brains were extracted. RNA extraction and qPCR analysis took place after a variable amount of time.

## 2.2 Behavioral Tests

Behavioral testing took place 130-131 days after the brooding mothers were placed into experimental conditions and consisted of two assays: boldness and social. Both assays were performed on the same day (Figure 2.2). Directly after each fish took part in the boldness assay, the brood was observed in the social assay. Prior to the start of behavioral testing, the focal brood was moved in its home tank to the testing area. The fish were allowed to acclimate to the change in lighting for 10 minutes. Fish were moved into the appropriate experimental tank (see below) for testing. A video camera was placed approximately two feet from the front side and no humans were present in the room during behavioral recordings. The recorded behavior was scored blind to the experimental condition using the video recordings.

**Boldness Assay**

Boldness, or willingness to explore novel and open environments, is often used as a

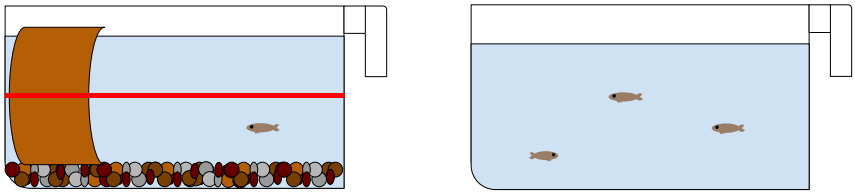

Figure 2.3: Behavioral paradigms.
Two paradigms were used to assess behavioral phenotypes of the fish. In the boldness assay (left) individual fish were placed in a novel tank containing gravel and a terra cotta shelter. After 10 minutes of habituation, time spent in the top half of the tank, in the bottom half of the tank, and behind the shelter was recorded for an additional 10 minutes. In the aggression assay (right) the whole brood was placed into a single, novel tank. As with the other assay, the fish were allowed to adjust to the change in environment for 10 minutes. The number of chases, charges, and bites between fish were recorded for 10 minutes.

measure of stress (Bannier et al., 2017; Francis et al., 1999). Animals that are stressed tend to freeze in place, seek cover, and avoid open spaces. Focal fish were individually placed in a novel experimental tank containing gravel and a terra cotta shelter. Three sides of the tank were covered in white paper to minimize external stimuli. A piece of red tape was horizontally placed on the outside of the tank, dividing it into top and bottom. The fish were allowed to acclimate for 10 minutes in the experimental tank before their behavior was scored for another 10 minutes. Time spent in three distinct areas of the tank were recorded: top half of tank, bottom half of the tank, under the shelter. The fish was considered to be in a given region once its eyes crossed the border.

### Aggression Assay

Because *A. burtoni* are highly social fish, it is relevant to assess how maternal separation affects their social behavior. Aggression is known to be tightly correlated with stress, thus measuring aggression within broods is important in analyzing their overall stress response (Gammie and Stevenson, 2006; Averli et al., 2004; Honess and

Marin, 2006; Takahashi et al., 2018). Individual broods were transferred into a novel tank containing only water. Three sides of the tank were covered in white paper to minimize external stimuli. The fish were allowed to acclimate to the new environment for 10 minutes before scoring began. The number of charges, bites, and chases between fish that occurred in 10 minutes was counted by hand (Table 2.2). The total sum of aggressive behaviors was then divided by the number of fish in the brood to create a score. Broods of only one fish in them were excluded from this paradigm.

Table 2.2: Aggression Ethogram

| **Behavior** | **Description** |
|---|---|
| Charge | Fry A increases swim speed in the direction of Fry B.<br>In response, Fry B moves to avoid Fry A. |
| Chase | Fry A swims towards Fry B. As Fry B swims away from Fry A,<br>Fry A follows the path of Fry B. |
| Bite | The rostral end of Fry A makes contact with Fry B.<br>Fry B reacts by swimming away from Fry A. |

## 2.3 Gene Expression Assay

Directly following behavioral testing, fish were measured for length and weight and quickly decapitated. The brains were then extracted and placed into 1 mL of RNALater and stored at 4 °C until needed for RNA isolation. RNA from each individual's whole brains was extracted using a Maxwell 16 LEV simplyRNA Tissue kit (Promega AS1270). RNA quality and concentration were confirmed using gel electrophoresis and nanodrop. For each sample, 100 ng of isolated RNA was reverse transcribed into cDNA with an Invitrogen Reverse Transcription kit (Thermo Fisher 18080093) (Figure 1.1).

Previously validated primers for GR1a, GR1b, and GR2 were used for qPCR (Solomon-Lane and Hofmann, 2018) (Figure 2.4). The reference gene rpl32, which is a ribosomal protein coding gene, was used as a reference for GR expression. Each re-

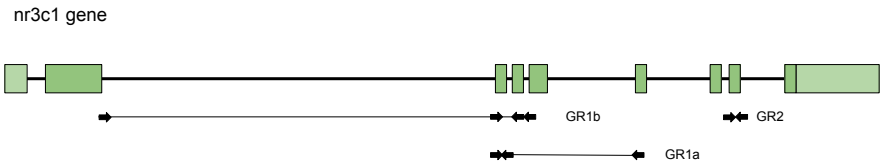


Figure 2.4: Primer design.
Primers sequences were taken from a study by Taborsky *et. al.* The locations of the primers were then found by comparing the sequences to *A. burtoni* transcriptional sequences using the NCBI BLAST database. The GR2 primer is designed to target the homologous duplicated GR receptor (nr3c1) gene. Primers that span introns are denoted by two arrows in the same direction.

action contained cDNA (1 $\mu$L), 2x Immuno Mix (10 $\mu$L), forward and reverse primers (1 $\mu$L of 100 nM each), 50x SYBR Green (0.5 $\mu$L), and nuclease-free water (6.5 $\mu$L). The program used for the qPCR reaction included a hot start (95°C, 5:00 min), 40 cycles that each ended with a fluorescent plate read (94°C, 0:45 min; 60.9°C, 1:00 min; 72°C, 0:30 min), 72°C for 2:00 min, and a melt curve analysis from 65°C to 95°C that measured fluorescence at 0.5°C intervals every five seconds. qPCR was run using a BioRad CFX Connect Real-Time PCR Detection System and the data were analyzed with CFX Manager software.

The starting quantity (SQ) for each sample was calculated by adjusting the cycle quantification ($C_q$) value by the efficiency of the primer in order to correct for starting concentration of cDNA. The mean SQ for each sample (samples were run in duplicate) was then divided by the mean SQ of rpl32.

Table 2.3: Genes and corresponding qPCR primer information

| Target | Forward Primer (5' to 3') | Reverse Primer (5' to 3') | Melting Temperature | Efficiency |
|---|---|---|---|---|
| gr2 | TGC CTC TGT CAC TGC CAC CGT AG | AGT CGT CTG CGT CTG AAG TAA CTG | 60.9 °C | 100.7% |
| gr1a | TCA TAA GAT CTG TTT GGT GTG CTC | GTA GTT GTG CTG GCC TTC AAC | 60.9 °C | 106.9% |
| gr1b | TGT TGG CTT CTC CGG TTC ATC AC | GTT GTG CTG GCC ATC TGT GTT T | 60.9 °C | 94.4% |
| rpl32 | TGC TGA TGC CCA ACA TCG GTT | TCT TGG AGG AGA CAT TGT GGG | 60.9 °C | 99.2 % |

**Troubleshooting**

Prior to working with experimental fish, an age-matched brood was used to troubleshoot behavioral testing. Following that, the brood was euthanized using MS-222 to practice brain extractions. Two of the extracted brains were used for gene expression troubleshooting. RNA was extracted from the brains and reverse transcribed into cDNA. All of the primer sets were tested using PCR on a gradient of melting temperature using this cDNA. The most effective melting temperature was then selected for qPCR. The efficiency of individual primers at the selected melting temperature was calculated with qPCR using a two-fold dilution series ranging from $2^0$ to $2^{-5}$ of the cDNA.

# Chapter 3

# Results

## 3.1 Size

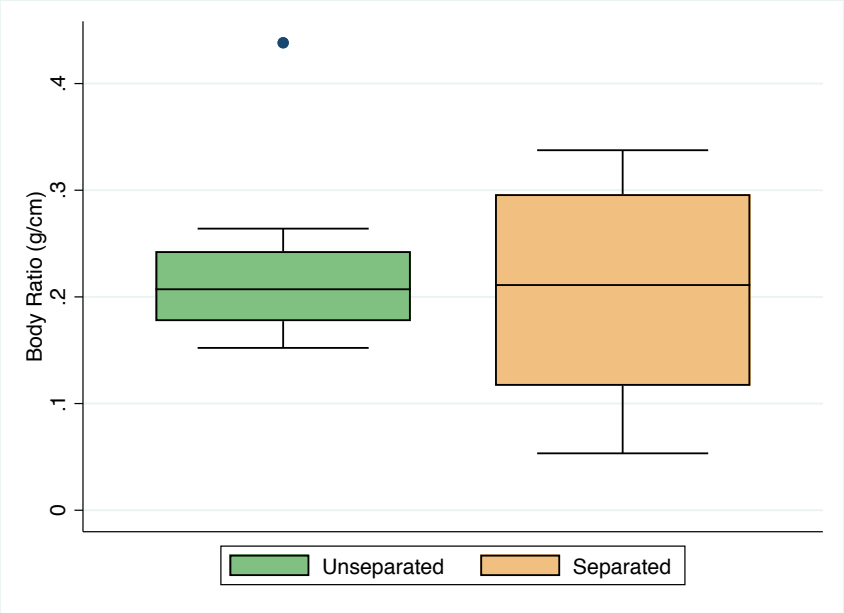


Figure 3.1: Comparison of fry body ratio by condition (medians and quartiles).
The body ratio of each fry was calculated as the body weight in grams divided by the standard length in centimeters. A Student's t-test determined that there was no statistically significant difference between the size of fry kept with their mothers (n=9) and fry separated from their mothers (n=9), $p$=0.25.

Because glucocorticoids alter development, each fry's body composition was as-

sessed. Prior to euthanasia each fry's weight and standard length were measured. Body ratio was calculated to be the weight divided by body length. The conditions were compared using a Student's t-test for independent means. There was no significant difference between fry kept with their mothers ($\overline{x}$=0.23 g/cm, $SD$=0.09) and fry separated from their mothers ($\overline{x}$=0.20 g/cm, $SD$=0.11), $t(16)$=0.70, $p$=0.25 (Figure 3.1). There was also no significant difference between the length alone (separated $\overline{x}$=2.31 cm, $SD$=0.66; unseparated $\overline{x}$=2.49 cm, $SD$=0.44), $t(16)$=0.67 , $p$=0.51; nor the weight alone (separated $\overline{x}$=0.52 g, $SD$=0.38; unseparated $\overline{x}$=0.60 g, $SD$=0.35) $t(16)$=0.46, $p$=0.65.

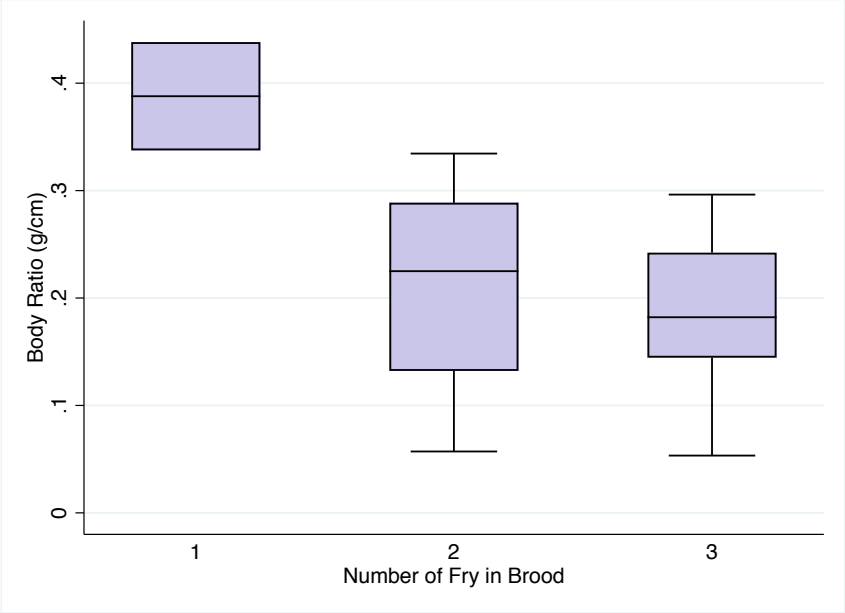


Figure 3.2: Comparison of fry body ratio by brood size (medians and quartiles).
Fry from broods containing only one fish (n=2) had a significantly higher body ratio compared to fry from broods with two (n=4) or three (n=12), as determined by a one-way ANOVA and post hoc Tukey HSD test, $p<0.05$.

A one-way ANOVA and Tukey HSD test were used to compare size based on number of fry in the brood. Broods in which there were only one fish ($\overline{x}$=0.39 g/cm, $SD$=0.07) were significantly greater in body ratio compared to broods with two ($\overline{x}$=0.21 g/cm, $SD$=0.12) or three ($\overline{x}$=0.19 g/cm, $SD$=0.07) fry, $F(2,15)$=5.34, $p<0.05$ (Figure 3.2). Additionally, broods with only one fry ($\overline{x}$=3.30 cm, $SD$=0.14)

were longer than broods with three fry ($\overline{x}$=2.23 cm, $SD$=0.39), $F(2,15)$=4.70, $p$<0.05; but not with two fry ($\overline{x}$=2.48 cm, $SD$=0.72). Further, fry from single broods ($\overline{x}$=1.29 g, $SD$=0.29) weighed more than fry from broods of two ($\overline{x}$=0.58 g, $SD$=0.37) or three ($\overline{x}$=0.44 g, $SD$=0.21) fry, $F(2,15)$=9.49, $p$<0.01.

## 3.2 Boldness

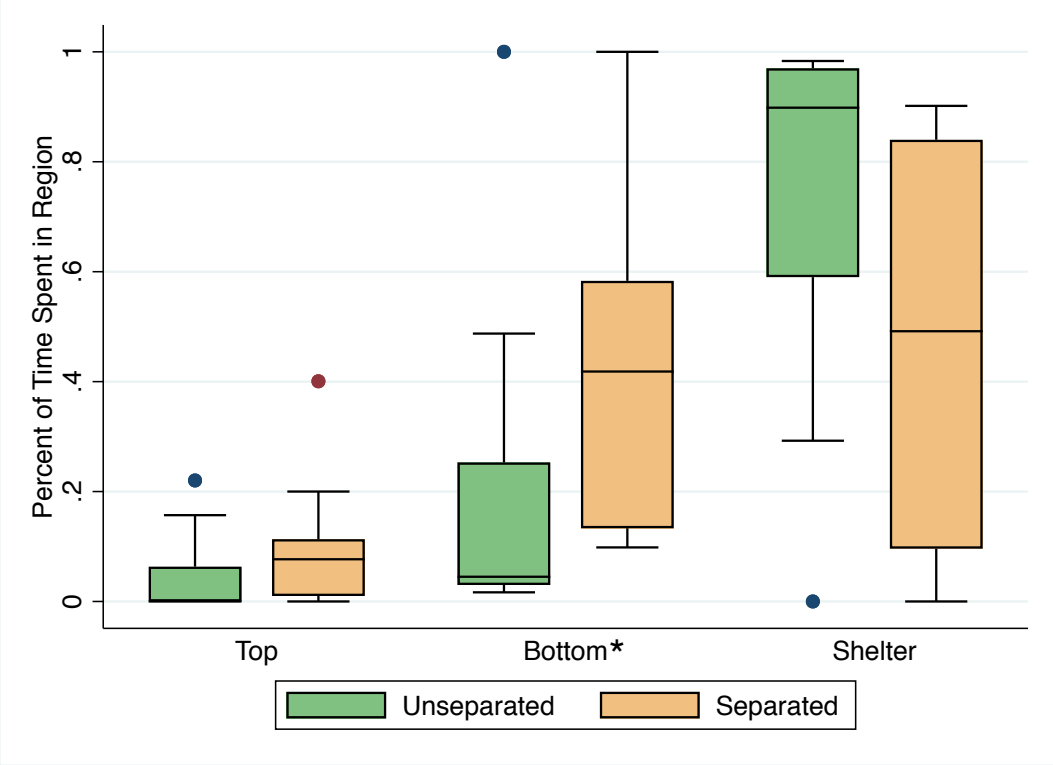


Figure 3.3: Effect of maternal separation on boldness (medians and quartiles).
Fry were placed individually into a novel tank divided into three parts: top, bottom, and shelter. The percent of time spent in each region over the course of 10 minutes was recorded. Student's t-tests were used to determine fry separated from their mothers (n=9) spent significantly more time in the bottom of the tank compared to those that were unseparated (n=9), $p$<0.05. There was no significant difference between groups for time spent in shelter ($p$=0.08) and in top ($p$=0.22).

The boldness assay is meant to assess the fry's anxiety-like behavior in a novel environment. The experimental tank was divided into three parts: the shelter, where fry could hide behind; the bottom of the tank, where fry were exposed, but could

blend in with the gravel; and the top of the tank, where fry were in completely open water. The data were non-normally distributed, so a Mann-Whitney test was used to analyze them. Fry that were separated from their mothers spent a significantly greater percentage of their time in the the bottom of the tank ($Mdn$=41.83%) compared to those unseparated from their mothers ($Mdn$=4.50%), $z$=-2.03, $p$<0.05. There was no significant difference between conditions in the time spent at the top (separated $Mdn$=7.68%, unseparated $Mdn$=0.00% ; $z$=-1.23, $p$=0.22) and behind the shelter (separated $Mdn$=49.17%, $Mdn$ unseparated=89.83%; $z$=1.77, $p$=0.08) (Figure 3.3).

## 3.3 Aggression

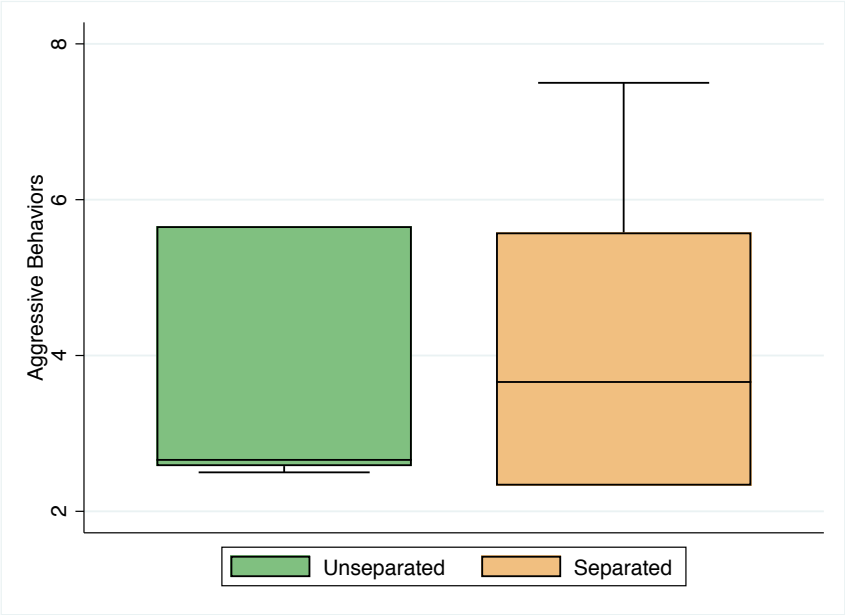


Figure 3.4: Comparison of tank aggression between groups (medians and quartiles).
Fry aggression was measured as the amount of charges, chases, and bites that occurred within 10 minutes, divided by the number of fry in the tank. Broods in which there was only one fry in the tank were not tested. As measured by a Mann-Whitney test, there was no difference between fry separated from their mothers (n=8) and fry kept with their mothers (n=8), $p$=0.92

To measure brood aggression, the total number of charges, chases, and bites were summed. This sum was then divided by the number of fry in the brood to calculate

an average aggression score that accounted for brood size. The resulting data were not normally distributed, so to analyze the aggression, a Mann-Whitney test was used. There was no significant difference in the number of attacks per fish between separated ($Mdn$=3.66) and unseparated ($Mdn$=2.66) groups, $z$=0.11, $p$=0.92 (Figure 3.4).

## 3.4 Glucocorticoid Receptor Expression

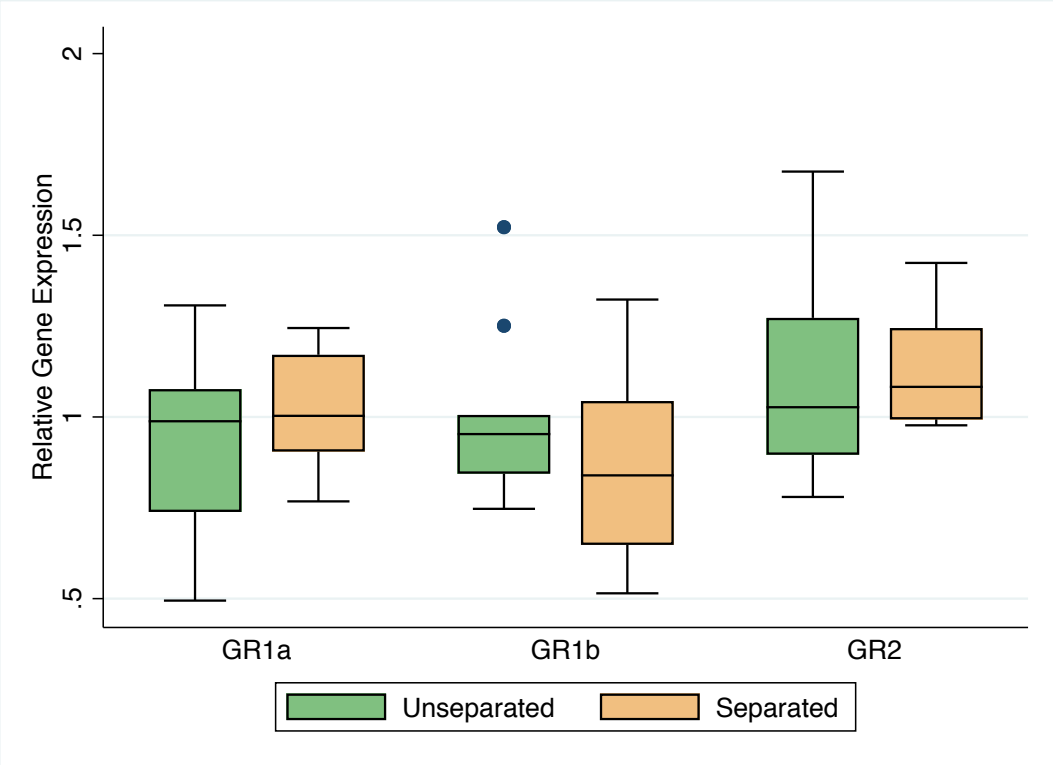


Figure 3.5: GR expression profile for experimental conditions (medians and quartiles). Relative expression for GR1a, GR1b, and GR2 were calculated by adjusting the $C_q$ by primer efficiency and then by dividing this starting quantity by starting quantity of the control gene rpl32. A linear mixed model was used to determine differences in expression level between conditions while taking into account brood effect. There was no significant difference in the expression levels between fry separated from their mothers (GR1a n=9, GR1b n=9, GR2 n=7) and fry brooded by their mothers (GR1a n=9, GR1b n=9, GR2 n=9); GR1a $p$=0.47, GR1b $p$=0.17, GR2 $p$=0.81.

GR1a, GR1b, and GR2 expression were analyzed using a linear mixed model that took into account brood effect.

There was no statistically significant gene expression between treatment groups for all three genes of interest (GR1a separated $\overline{x}$=1.02, unseparated $\overline{x}$=0.92, $t(16)$=0.78, $p$=0.47; GR1b separated $\overline{x}$=0.86, unseparated $\overline{x}$=1.00, $t(16)$=-1.44 $p$=0.17; GR2 separated $\overline{x}$=1.14, unseparated $\overline{x}$=1.12, $t(14)$=0.26, $p$=0.81) (Figure 3.5).

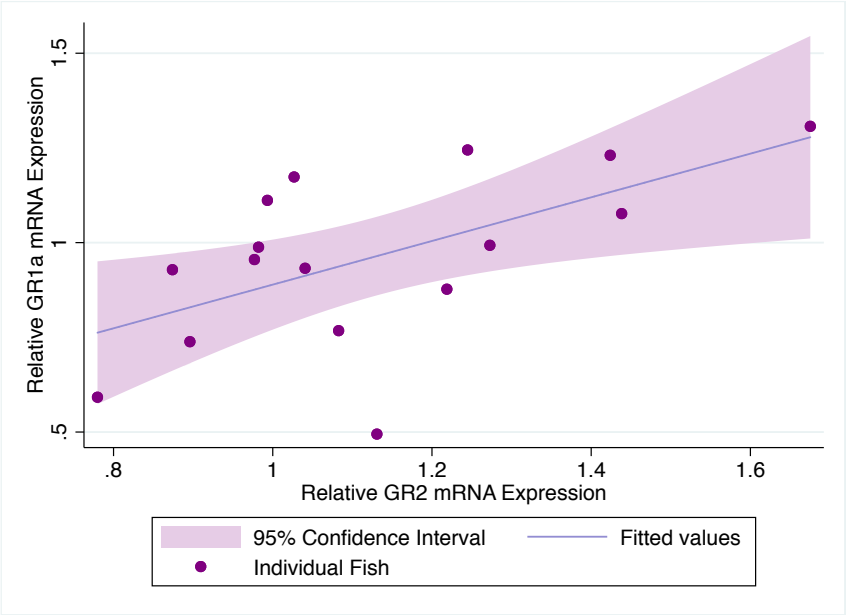


Figure 3.6: Relationship between GR1a and GR2 expression.
GR1a expression was positively correlated with GR2 expression (N=16), $p$<0.05.

There was a statistically significant correlation between GR1a and GR2 ($r$=0.35, $p$<0.05) receptor expression and between GR1b and GR2 ($r$=0.30,$p$<0.05) receptor expression (Figure 3.6 and 3.7 respectively). Additionally, GR2 expression was negatively correlated with length of fry ($r$=0.31, $p$<0.05) (Figure 3.8).

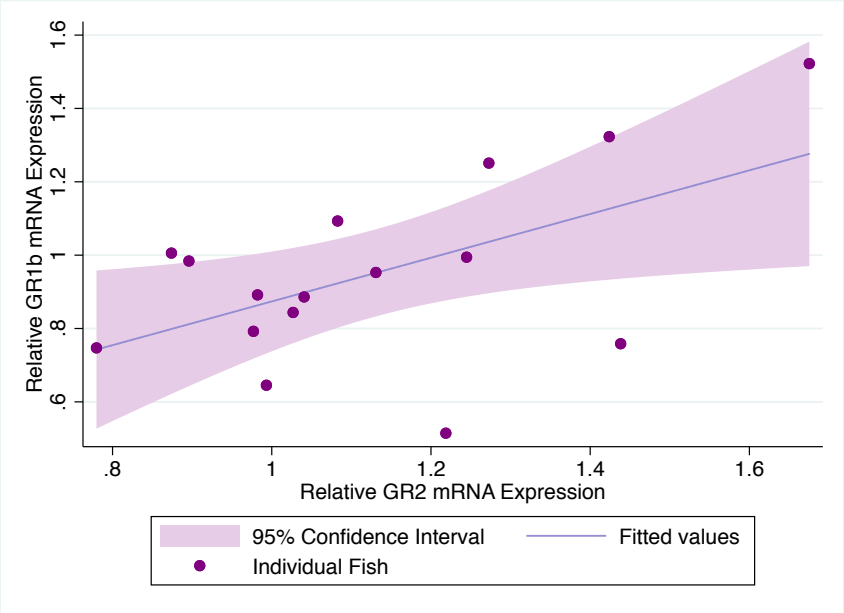


Figure 3.7: Relationship between GR1b and GR2 expression
GR1b expression was positively correlated with GR2 expression (N=16), $p<0.05$

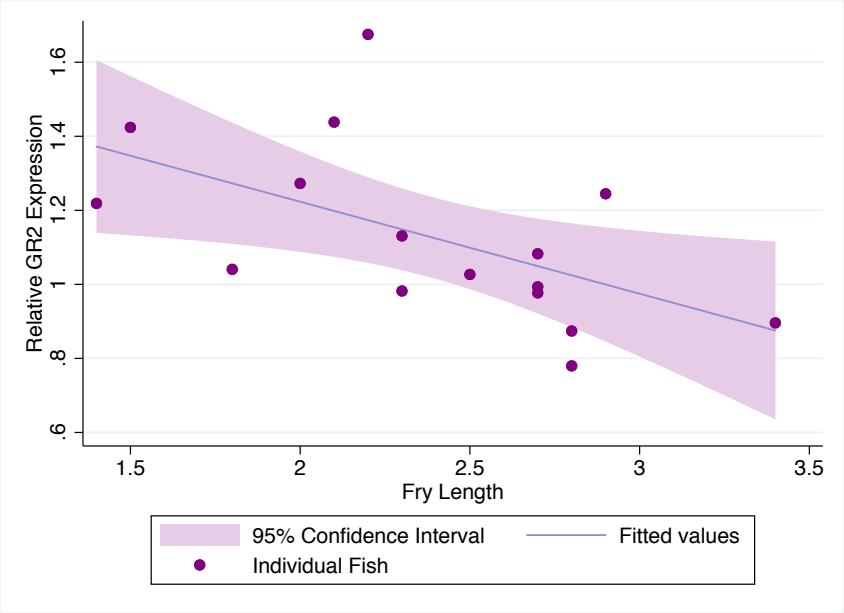


Figure 3.8: Negative correlation between fry standard length and GR2 expression.
The standard length of the fry was negatively correlated with GR2 expression (N=16), $p<0.05$.

# Chapter 4

# Discussion

In humans, early-life stress is known to be tightly connected to adverse health outcomes including addiction, depression, anxiety, PTSD, obesity, oxidative stress, mortality, and more (Gilbert et al., 2009; Repetti et al., 2002; Anda et al., 2006; Heim and Nemeroff, 2001; Essex et al., 2002). Understanding the mechanism by which early-life experience translates to changes in neurophysiology is crucial to developing treatments to help survivors of traumatic childhood experiences. The use of animal models for human conditions offers an efficient and tightly controlled way in which to examine behavior and physiology.

Differences in maternal care are a common way to model early-life stress in animals (Bolton et al., 2017). In rats, high levels of licking and grooming lead to an increase in learning and memory, a decrease in anxiety-like behavior, and an increase in hippocampal GR expression (Herman et al., 2005; Caldji et al., 1998). This increase in GR expression is thought to increase inhibitory feedback onto the HPA axis, thus decreasing the pups' responsiveness to stressful stimuli (van Bodegom et al., 2017). The inverse of these observations is true of pups reared by low maternal care mothers, with pups displaying a heightened responsiveness to their stressful environment (Liu et al., 2000; Caldji et al., 1998). Although these pups have decreased learning and memory

in non-stressful conditions, they have an increase in learning and memory in stressful conditions compared to their high maternal care counterparts (Champagne et al., 2008). This suggests that the stress response adapts to better fit the environment. In support of this concept, is the finding that rat mothers in stressful environments have lower maternal care and thus produce pups with heightened responsiveness (Francis et al., 1999; Champagne and Meaney, 2006). The rat model of maternal care is an example of how early life stress can alter the adult animal's responsiveness to stress.

I was interested in analyzing whether this model of early-life stress can be paralleled in fish. While most biomedical research relies on the use of mammalian models, fish models are growing in popularity due to the fact that they share a large amount of gene functionality with humans and are much more cost-effective (Cech and Zon, 2011). *A. burtoni* are a logical candidate for modeling the effects that differences in maternal care have on the stress response because of their phenotypic plasticity, similar stress response circuitry, and maternal mouthbrooding behavior (Greenwood et al., 2003; Pijanowski et al., 2015; Renn et al., 2008).

While the impact of maternal care on offspring stress response isn't well studied in fish, it has been shown that early life social experience can influence cichlid stress response (Nyman et al., 2017; Arnold and Taborsky, 2010). *N. pulcher* fry raised in the absence of adults have decreased telencephalic GR1a expression and higher aggression. In contrast, fish reared in the naturalistic social groups with adults and helper fish have reduced aggression and increased telencephalic GR1a expression (Nyman et al., 2018; Bannier et al., 2017). This work in *N. pulcher* demonstrates that cichlids are plastic to their early-life environments, and thus may be a good model of early-life stress.

Early life stress in *A. burtoni* was modelled through maternal separation and measured by the offspring stress response through two behavioral paradigms and a GR expression assay. Fry separated from their mothers spent a significantly greater

amount of time in the bottom of the novel tank; although, the amount of time spent in the top of the tank and behind the shelter did not differ between experimental conditions. While the two conditions did not differ in size, fish from broods of one fry had a significantly greater body ration and length compared to fish from broods of two or three fry. There was no significant difference in aggression or GR expression levels between the conditions. Notably, there was a positive correlation between GR2 expression and GR1a expression, as well as a positive correlation between GR2 expression and GR1b expression. There was also a negative correlation between GR2 expression and fry length.

The finding that fish separated from their mothers spent more time in the bottom of the novel tank is difficult to assess without considering the trends in time spent in the top and bottom of the tank. Spending time behind the shelter would be indicative of anxiety-like behavior because teleosts, including *A. burtoni* in conditions known to produce a stress response prefer dark spaces, spend more time at the bottom of the tank, and avoid open areas, often clinging to walls (Gould, 2011; Neumeister et al., 2017; Ansai et al., 2016; Norton and Gutiérrez, 2019; Ghisleni et al., 2012). For the opposite reason, spending time in the top of the tank is indicative of reduced stress. The bottom region, however, is open to the overhead lights; is more open than the shelter, but less open than the top; and also provides gravel as camouflage. Because there is a trend toward separated fry spending more time in the top and less time behind the shelter, as compared to unseparated fry, the increased time spent at the bottom of the tank can be interpreted as increased boldness. This is counter to the hypothesis that fry separated from their mothers would exhibit more anxiety-like behavior and thus stay hidden behind the shelter. Boldness has been shown to be influenced by both learned avoidance and by mother's experience (Brown et al., 2007). Given this finding it is possible that the fry in the brooded group were able to learn avoidance of open spaces from their mothers.

There was no significant difference in aggression between groups. This is unlike the finding by Taborsky that *N. pulcher* raised without adults have higher levels of aggression compared to those raised with adults (Arnold and Taborsky, 2010). It is possible that the fry in the present study were too young to express the distinct social behaviors seen in adults, as they were tested at an age on the brink of maturity (Fernald, 1977). Another possible confound is that the most aggressive fry killed all of their siblings and thus couldn't be included in the analysis.

Approximately half of the video recordings for the behavioral assays were lost, making additional analysis impossible. In addition to time spent in open spaces as an indicator of reduced stress, the degree of exploration in a novel space is also indicative of reduced stress (Bannier et al., 2017). For this reason, it would have been useful to have a count of entries into each of the regions for the boldness assay as well as a measure of total distance travelled. In the aggression assay, it would be helpful to have assigned each individual fish an aggression score rather than averaging the whole brood. It is possible that while there was no correlation between average brood aggression and GR expression, there could have been a correlation between individual aggression and expression.

Additional methods for measuring stress response regulation can be used in order to gain a better understanding of the ways in which maternal separation is affecting the HPA axis. Like GRs, mineralocorticoid receptors bind corticosteroids and are down regulated in animals exposed to early life stress (Gass et al., 2001; Meaney et al., 1996). In addition to receptor expression, circulating hormones can be used as a measure of HPA-axis activation. As mentioned before, fish with low stress early in life have lower CRH levels due to both decreased hypothalamic activation and increased hypothalamic negative feedback via GR activation (Taborsky et al., 2012). The extent of negative regulation within the HPA axis can be tested by exposing the fry to excess cortisol and measuring their subsequent CRH levels (Liu et al., 2000).

Cortisol can also be a way to measure HPA axis regulation, as greater inhibition of the axis is associated with lower circulating cortisol in response to a stressor (Liu et al., 2000).

Given that the work of Michael Meaney primarily models maternal care and not maternal separation, it may be worth altering the experimental conditions to better mirror the rat model. One potential measure of maternal care in *A. burtoni* is filial cannibalism. Lab stock mothers exhibit higher instances of cannibalizing their young compared to wild stock mothers. This is likely as a result of the artificial separation of fry and mothers within lab stock leading to a decrease in selective pressure for kin selection (Renn et al., 2009; Lonstein and Gammie, 2002). This measure is of course not useful in a study dependent on observing the phenotypes of fry; however, the distance between fry and mother after initial release is a measure correlated with filial cannibalism that can be used instead. A preliminary study by the Renn lab found that wild stock mothers stay significantly closer in proximity to their fry compared lab stock mothers. This measure of maternal care would be useful if there is notable variation within a single stock, since using wild stock as the high maternal care group and lab stock as the low maternal care group would introduce a number of other variables associated with differences in genotype and phenotype that exist between the groups. The use of maternal proximity also has the advantage of being a naturally occurring phenotype in contrast to the induced maternal separation condition in the focal experiment.

Although there was no difference in GR expression between conditions, there were correlations between GR1a expression and GR2 expression and between GR1b expression and GR2 expression. This implies that there are fish with distinct and consistent GR expression profiles. In the present study, not all variables that can influence GR expression were accounted for. For one, sex is known to influence the degree of HPA-axis regulation that occurs in response to early life stress. Female rats

exhibit a larger change in HPA axis function in response to early life stress compared to males (McCormick et al., 1995).

In light of the correlation between standard length and GR2 expression in the focal fry, it is possible that social conditions were much more influential on GR expression than maternal separation was. While fry length is not a direct measure of dominance, relative size of a male in a social group is a primary predictor of social rank (Hofmann et al., 1999). Given that *A. burtoni* are highly social fish in which social status determines reproductive fitness and access to food, behavioral plasticity in response to hierarchical ranking is adaptive (Fox et al., 1997). In adults, dominant males have an increase in GR1a and GR2 expression in the preoptic area compared to non-dominant males (Korzan et al., 2014). While the study was interested in this brain region due to its involvement in sexual behavior, the preoptic area also has an inhibitory effect on the HPA-axis by reducing ACTH release (Herman et al., 2004).

These results seem to contradict the current finding that fry length is negatively correlated with GR2 expression; however, this contrast is consistent with the literature when considering the differences in methods. A recent study found that *A. burtoni* fry raised in pairs had decreased whole-brain GR1a expression compared to fry raised in groups (Solomon-Lane and Hofmann, 2018). While inhibitory regions of the brain, like the hippocampus and preoptic area, have increased GR expression throughout the brain in response to early-life stress, the net level GR expression may actually decrease in response to stress. GRs have a wide range of transcriptional effects besides those related to HPA axis regulation (Busada and Cidlowski, 2017). If early-life stress decreases HPA axis inhibition through decreased regulatory GR expression, it follows that an increase in the GR expression of receptors that actually aid in reallocating energy towards an inflammatory response or escape behavior would increase. This is supported by the finding that there is an increase in circulating cortisol, a major ligand for GRs, in animals exposed to early-life stress (Essex et al., 2002; Zhang and

Meaney, 2010).

A future study interested in using *A. burtoni* to model early-life stress could examine specific regulatory regions of the brain. Complicating this possibility is the fact that the telencephalic pallium and medial pallium of *A. burtoni* — regions expected be responsive to early life stress — are much smaller than the homologous structures in rats (hippocampus and amygdala respectively) and thus hard to isolate (Salas et al., 2006). Additionally, there is not a clear homologue of the mammalian prefrontal cortex, a region known to be heavily affected by fluctuations in glucocorticoids, in teleosts (Lupien et al., 2009; Yamamoto, 2009).

Using *A. burtoni* as a model organism for studying early life stress offers a high throughput way to examine a complex condition. The present study found that maternal separation did not impact the overall stress response of fry, though different methods should be used to confirm these findings. To better mirror studies done in mammals, a maternal care assessment could be developed in place of maternal separation. The finding that size influences GR2 expression supports evidence that early-life social experience contributes to the adult stress response; however, further research is needed to understand the brain-specific changes in GR expression. In sum, *A. burtoni* have distinct GR expression profiles that appear to be mediated by their early-life environment, though not through maternal separation. Given the large influence that early-life stress exposure has on the developing brain and body, it is important to continue research that uncovers reprogramming of the HPA axis.

# References


Anda, R. F., Felitti, V. J., Bremner, J. D., Walker, J. D., Whitfield, C., Perry, B. D., Dube, S. R., and Giles, W. H. (2006). The enduring effects of abuse and related adverse experiences in childhood: A convergence of evidence from neurobiology and epidemiology. *European Archives of Psychiatry and Clinical Neuroscience*, 256(3):174–186.

Ansai, S., Hosokawa, H., Maegawa, S., and Kinoshita, M. (2016). Chronic fluoxetine treatment induces anxiolytic responses and altered social behaviors in medaka, Oryzias latipes. *Behavioural Brain Research*, 303:126–136.

Arnold, C. and Taborsky, B. (2010). Social experience in early ontogeny has lasting effects on social skills in cooperatively breeding cichlids. *Animal Behaviour*, 79(3):621–630.

Averli, A., Korzan, W. J., Larson, E. T., Winberg, S., Lepage, O., Pottinger, T. G., Renner, K. J., and Summers, C. H. (2004). Behavioral and neuroendocrine correlates of displaced aggression in trout. *Hormones and Behavior*, 45(5):324–329.

Bannier, F., Tebbich, S., and Taborsky, B. (2017). Early experience affects learning performance and neophobia in a cooperatively breeding cichlid. *Ethology*, 123(10):712–723.

Barry, T. P., Malison, J. A., Held, J. A., and Parrish, J. J. (1995). Ontogeny of the cortisol stress response in larval rainbow trout. *General and Comparative Endocrinology*, 97(1):57–65.

Bayerl, D. S. and Bosch, O. J. (2019). Brain vasopressin signaling modulates aspects of maternal behavior in lactating rats. *Genes, Brain and Behavior*, 18(1):e12517.

Bolton, J. L., Molet, J., Ivy, A., and Baram, T. Z. (2017). New insights into early-life stress and behavioral outcomes. *Current Opinion in Behavioral Sciences*, 14:133–139.

Bolton, J. L., Short, A. K., Simeone, K. A., Daglian, J., and Baram, T. Z. (2019). Programming of Stress-Sensitive Neurons and Circuits by Early-Life Experiences. *Frontiers in Behavioral Neuroscience*, 13.

Border, S. E., Piefke, T. J., Fialkowski, R. J., Tryc, M. R., Funnell, T. R., DeOliveira, G. M., and Dijkstra, P. D. (2019). Color change and pigmentation in a color polymorphic cichlid fish. *Hydrobiologia*, 832(1):175–191.

Brown, C., Burgess, F., and Braithwaite, V. A. (2007). Heritable and experiential effects on boldness in a tropical poeciliid. *Behavioral Ecology and Sociobiology*, 62(2):237–243.

Busada, J. T. and Cidlowski, J. A. (2017). *Nuclear receptors in development and disease*. Current topics in developmental biology ; v. 125. Elsevier Academic Press, Cambridge, MA.

Caldji, C., Hellstrom, I. C., Zhang, T.-Y., Diorio, J., and Meaney, M. J. (2011). Environmental regulation of the neural epigenome. *FEBS Letters*, 585(13):2049–2058.

Caldji, C., Tannenbaum, B., Sharma, S., Francis, D., Plotsky, P. M., and Meaney, M. J. (1998). Maternal care during infancy regulates the development of neural systems mediating the expression of fearfulness in the rat. *Proceedings of the National Academy of Sciences of the United States of America*, 95(9):5335–5340.

Cech, J. and Zon, L. (2011). CELLULAR, MOLECULAR, GENOMICS, AND BIOMEDICAL APPROACHES | Fish as Model Organisms for Medical Research. In *Encyclopedia of Fish Physiology*, pages 1986–1997. Elsevier.

Champagne, D. L., Bagot, R. C., van Hasselt, F., Ramakers, G., Meaney, M. J., de Kloet, E. R., Joels, M., and Krugers, H. (2008). Maternal Care and Hippocampal Plasticity: Evidence for Experience-Dependent Structural Plasticity, Altered Synaptic Functioning, and Differential Responsiveness to Glucocorticoids and Stress. *Journal of Neuroscience*, 28(23):6037–6045.

Champagne, F. A. and Meaney, M. J. (2006). Stress During Gestation Alters Postpartum Maternal Care and the Development of the Offspring in a Rodent Model. *Biological Psychiatry*, 59(12):1227–1235.

Crick, F. (1955). On Degenerate Templates and the Adaptor Hypothesis.

Crick, F. (1958). On Protein Synthesis. *Cambridge University Press*, 12:138–163.

Essex, M. J., Klein, M. H., Cho, E., and Kalin, N. H. (2002). Maternal stress beginning in infancy may sensitize children to later stress exposure: effects on cortisol and behavior. *Biological Psychiatry*, 52(8):776–784.

Faught, E., Best, C., and Vijayan, M. M. (2016). Maternal stress-associated cortisol stimulation may protect embryos from cortisol excess in zebrafish. *Royal Society Open Science*, 3(2):160032.

Fernald, R. D. (1977). Quantitative behavioural observations of Haplochromis burtoni under semi-natural conditions. *Animal Behaviour*, 25:643–653.

Fernald, R. D. and Maruska, K. P. (2012). Social information changes the brain. *Proceedings of the National Academy of Sciences*, 109(Supplement_2):17194–17199.

Fox, H. E., White, S. A., Kao, M. H. F., and Fernald, R. D. (1997). Stress and Dominance in a Social Fish. *The Journal of Neuroscience*, 17(16):6463–6469.

Francis, D., Diorio, J., Liu, D., and Meaney, M. J. (1999). Nongenomic transmission across generations of maternal behavior and stress responses in the rat. *Science (New York, N.Y.)*, 286(5442):1155–1158.

Francis, R. C., Soma, K., and Fernald, R. D. (1993). Social regulation of the brain-pituitary-gonadal axis. *Proceedings of the National Academy of Sciences of the United States of America*, 90(16):7794–7798.

Freire, Paulo, .-. ([2000]). *Pedagogy of the oppressed*. Thirtieth anniversary edition. New York : Continuum, [2000] ©2000.

Galton, F. (1874). *English Men of Science: Their Nature and Nurture*. Macmillan & Co., London.

Gammie, S. C. and Stevenson, S. A. (2006). Effects of daily and acute restraint stress during lactation on maternal aggression and behavior in mice. *Stress*, 9(3):171–180.

Gass, P., Reichardt, H. M., Strekalova, T., Henn, F., and Tronche, F. (2001). Mice with targeted mutations of glucocorticoid and mineralocorticoid receptors: Models for depression and anxiety? *Physiology & Behavior*, 73(5):811–825.

Ghisleni, G., Capiotti, K. M., Da Silva, R. S., Oses, J. P., Piato, A. L., Soares, V., Bogo, M. R., and Bonan, C. D. (2012). The role of CRH in behavioral responses to acute restraint stress in zebrafish. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, 36(1):176–182.

Gilbert, R., Widom, C. S., Browne, K., Fergusson, D., Webb, E., and Janson, S. (2009). Burden and consequences of child maltreatment in high-income countries. *The Lancet*, 373(9657):68–81.

Glasauer, S. M. K. and Neuhauss, S. C. F. (2014). Whole-genome duplication in teleost fishes and its evolutionary consequences. *Molecular Genetics and Genomics*, 289(6):1045–1060.

Gluckman, P. D., Hanson, M. A., and Beedle, A. S. (2007). Early life events and their consequences for later disease: A life history and evolutionary perspective. *American Journal of Human Biology*, 19(1):1–19.

Gould, G. G. (2011). *Aquatic Light/Dark Plus Maze Novel Environment for Assessing Anxious Versus Exploratory Behavior in Zebrafish (Danio rerio) and Other Small Teleost Fish*, pages 99–108. Humana Press, Totowa, NJ.

Gravanis, A. G. and Mellon, S. H., editors (2011). *Hormones in neurodegeneration, neuroprotection, and neurogenesis*. Wiley-Blackwell, Weinheim, Germany. OCLC: ocn707710803.

Greenwood, A. K., Butler, P. C., White, R. B., DeMarco, U., Pearce, D., and Fernald, R. D. (2003). Multiple Corticosteroid Receptors in a Teleost Fish: Distinct Sequences, Expression Patterns, and Transcriptional Activities. *Endocrinology*, 144(10):4226–4236.

Harris, M. P., Henke, K., Hawkins, M. B., and Witten, P. E. (2014). Fish is Fish: the use of experimental model species to reveal causes of skeletal diversity in evolution and disease. *Zeitschrift Fur Angewandte Ichthyologie = Journal of Applied Ichthyology*, 30(4):616–629.

Heim, C. and Nemeroff, C. B. (2001). The role of childhood trauma in the neurobiology of mood and anxiety disorders: preclinical and clinical studies. *Biological Psychiatry*, 49(12):1023–1039.

Herman, J. P., McKlveen, J. M., Ghosal, S., Kopp, B., Wulsin, A., Makinson, R., Scheimann, J., and Myers, B. (2016). Regulation of the Hypothalamic-Pituitary-Adrenocortical Stress Response. In Terjung, R., editor, *Comprehensive Physiology*, pages 603–621. John Wiley & Sons, Inc., Hoboken, NJ, USA.

Herman, J. P., Mueller, N. K., and Figueiredo, H. (2004). Role of GABA and Glutamate Circuitry in Hypothalamo-Pituitary-Adrenocortical Stress Integration. *Annals of the New York Academy of Sciences*, 1018(1):35–45.

Herman, J. P., Ostrander, M. M., Mueller, N. K., and Figueiredo, H. (2005). Limbic system mechanisms of stress regulation: Hypothalamo-pituitary-adrenocortical axis. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, 29(8):1201–1213.

Hershey, A. D. and Chase, M. (1952). Independent functions of viral protein and nucleic acid in growth of bacteriophage. *The Journal of General Physiology*, 36(1):39–56.

Hofmann, H. A., Benson, M. E., and Fernald, R. D. (1999). Social status regulates growth rate: Consequences for life-history strategies. *Proceedings of the National Academy of Sciences*, 96(24):14171–14176.

Honess, P. and Marin, C. (2006). Behavioural and physiological aspects of stress and aggression in nonhuman primates. *Neuroscience & Biobehavioral Reviews*, 30(3):390–412.

Jaenisch, R. and Bird, A. (2003a). Epigenetic regulation of gene expression: how the genome integrates intrinsic and environmental signals. *Nature Genetics*, 33(S3):245–254.

Jaenisch, R. and Bird, A. (2003b). Epigenetic regulation of gene expression: how the genome integrates intrinsic and environmental signals. *Nature Genetics*, 33(S3):245–254.

Jawahar, M. C., Murgatroyd, C., Harrison, E. L., and Baune, B. T. (2015). Epigenetic alterations following early postnatal stress: a review on novel aetiological mechanisms of common psychiatric disorders. *Clinical Epigenetics*, 7(1).

Jašarević, E., Rodgers, A. B., and Bale, T. L. (2015). A novel role for maternal stress and microbial transmission in early life programming and neurodevelopment. *Neurobiology of Stress*, 1:81–88.

Jenkins, S., Harker, A., and Gibb, R. (2018). Maternal Preconception Stress Alters Prefrontal Cortex Development in Long–Evans Rat Pups without Changing Maternal Care. *Neuroscience*, 394:98–108.

Keller-Wood, M. (2015). Hypothalamic-Pituitary-Adrenal Axis-Feedback Control. In Terjung, R., editor, *Comprehensive Physiology*, pages 1161–1182. John Wiley & Sons, Inc., Hoboken, NJ, USA.

Kim, E. J., Pellman, B., and Kim, J. J. (2015). Stress effects on the hippocampus: a critical review. *Learning & Memory*, 22(9):411–416.

Klengel, T., Mehta, D., Anacker, C., Rex-Haffner, M., Pruessner, J. C., Pariante, C. M., Pace, T. W. W., Mercer, K. B., Mayberg, H. S., Bradley, B., Nemeroff, C. B., Holsboer, F., Heim, C. M., Ressler, K. J., Rein, T., and Binder, E. B. (2013). Allele-specific FKBP5 DNA demethylation mediates gene–childhood trauma interactions. *Nature Neuroscience*, 16(1):33–41.

Koltzoff, N. (1934). THE STRUCTURE OF THE CHROMOSOMES IN THE SALIVARY GLANDS OF DROSOPHILA. *Science*, 80(2075):312–313.

Korzan, W. J., Grone, B. P., and Fernald, R. D. (2014). Social regulation of cortisol receptor gene expression. *Journal of Experimental Biology*, 217(18):3221–3228.

Kouzarides, T. (2007). Chromatin Modifications and Their Function. *Cell*, 128(4):693–705.

Krenik, D. (2018). The effects of maternal care on glucocorticoid receptor expression in the mouthbrooding chichlid a. burtoni.

Krubitzer, L. and Kahn, D. M. (2003). Nature versus nurture revisited: an old idea with a new twist. *Progress in Neurobiology*, 70(1):33–52.

Lakehayli, S., Said, N., Battas, O., Hakkou, F., and Tazi, A. (2015). Prenatal stress alters sensitivity to benzodiazepines in adult rats. *Neuroscience Letters*, 591:187–191g.

Lapp, H. E., Bartlett, A. A., and Hunter, R. G. (2019). Stress and glucocorticoid receptor regulation of mitochondrial gene expression. *Journal of Molecular Endocrinology*, pages R121–R128.

Lesuis, S. L., Lucassen, P. J., and Krugers, H. J. (2019). Early life stress impairs fear memory and synaptic plasticity; a potential role for GluN2b. *Neuropharmacology*, 149:195–203.

Liu, D., Diorio, J., Day, J. C., Francis, D. D., and Meaney, M. J. (2000). Maternal care, hippocampal synaptogenesis and cognitive development in rats. *Nature Neuroscience*, 3(8):799–806.

Liu, D., Diorio, J., Tannenbaum, B., Caldji, C., Francis, D., Freedman, A., Sharma, S., Pearson, D., Plotsky, P. M., and Meaney, M. J. (1997). Maternal care, hippocampal glucocorticoid receptors, and hypothalamic-pituitary-adrenal responses to stress. *Science (New York, N.Y.)*, 277(5332):1659–1662.

Lonstein, J. S. and Gammie, S. C. (2002). Sensory, hormonal, and neural control of maternal aggression in laboratory rodents. *Neuroscience & Biobehavioral Reviews*, 26(8):869–888.

Lorenz, M. G. and Wackernagel, W. (1994). Bacterial gene transfer by natural genetic transformation in the environment. *Microbiological Reviews*, 58(3):563–602.

Lu, N. Z., Collins, J. B., Grissom, S. F., and Cidlowski, J. A. (2007). Selective Regulation of Bone Cell Apoptosis by Translational Isoforms of the Glucocorticoid Receptor. *Molecular and Cellular Biology*, 27(20):7143–7160.

Lupien, S. J., McEwen, B. S., Gunnar, M. R., and Heim, C. (2009). Effects of stress throughout the lifespan on the brain, behaviour and cognition. *Nature Reviews Neuroscience*, 10(6):434–445.

Maruska, K., Soares, M. C., Lima-Maximino, M., Henrique de Siqueira-Silva, D., and Maximino, C. (2019). Social plasticity in the fish brain: Neuroscientific and ethological aspects. *Brain Research*, 1711:156–172.

McCormick, C. M., Smythe, J. W., Sharma, S., and Meaney, M. J. (1995). Sex-specific effects of prenatal stress on hypothalamic-pituitary-adrenal responses to stress and brain glucocorticoid receptor density in adult rats. *Developmental Brain Research*, 84(1):55–61.

McGowan, P. O., Sasaki, A., D'Alessio, A. C., Dymov, S., Labonté, B., Szyf, M., Turecki, G., and Meaney, M. J. (2009). Epigenetic regulation of the glucocorticoid receptor in human brain associates with childhood abuse. *Nature Neuroscience*, 12(3):342–348.

Meaney, M. J. (2006). Nature, Nurture, and the Disunity of Knowledge. *Annals of the New York Academy of Sciences*, 935(1):50–61.

Meaney, M. J., Diorio, J., Francis, D., Widdowson, J., LaPlante, P., Caldji, C., Sharma, S., Seckl, J. R., and Plotsky, P. M. (1996). Early environmental regulation of forebrain glucocorticoid receptor gene expression: implications for adrenocortical responses to stress. *Developmental Neuroscience*, 18(1-2):49–72.

Murmu, M. S., Salomon, S., Biala, Y., Weinstock, M., Braun, K., and Bock, J. (2006). Changes of spine density and dendritic complexity in the prefrontal cortex in offspring of mothers exposed to stress during pregnancy. *European Journal of Neuroscience*, 24(5):1477–1487.

Neumeister, H., Adelman, M., Gallagher, W., Gou, J., Merrins, K., Perkowski, M., Shih, S., Terranova, B., and Preuss, T. (2017). Socially induced plasticity in sensorimotor gating in the African cichlid fish Astatotilapia burtoni. *Behavioural Brain Research*, 332:32–39.

Norton, W. H. J. and Gutiérrez, H. C. (2019). The three-spined stickleback as a model for behavioural neuroscience. *PLOS ONE*, 14(3):e0213320.

Nyman, C., Fischer, S., Aubin-Horth, N., and Taborsky, B. (2017). Effect of the early social environment on behavioural and genomic responses to a social challenge in a cooperatively breeding vertebrate. *Molecular Ecology*, 26(12):3186–3203.

Nyman, C., Fischer, S., Aubin-Horth, N., and Taborsky, B. (2018). Evolutionary conserved neural signature of early life stress affects animal social competence. *Proceedings of the Royal Society B: Biological Sciences*, 285(1871):20172344.

Oakley, R. H. and Cidlowski, J. A. (2013). The biology of the glucocorticoid receptor: New signaling mechanisms in health and disease. *Journal of Allergy and Clinical Immunology*, 132(5):1033–1044.

Pastor, V., Pallarés, M. E., and Antonelli, M. C. (2018). Prenatal stress increases adult vulnerability to cocaine reward without affecting pubertal anxiety or novelty response. *Behavioural Brain Research*, 339:186–194.

Perlman, R. L. (2016). Mouse Models of Human Disease: An Evolutionary Perspective. *Evolution, Medicine, and Public Health*, page eow014.

Pijanowski, L., Jurecka, P., Irnazarow, I., Kepka, M., Szwejser, E., Verburg-van Kemenade, B. M. L., and Chadzinska, M. (2015). Activity of the hypothalamus–pituitary–interrenal axis (HPI axis) and immune response in carp lines with different susceptibility to disease. *Fish Physiology and Biochemistry*, 41(5):1261–1278.

Renn, S. C., Fraser, E. J., Aubin-Horth, N., Trainor, B. C., and Hofmann, H. A. (2012). Females of an African cichlid fish display male-typical social dominance behavior and elevated androgens in the absence of males. *Hormones and Behavior*, 61(4):496–503.

Renn, S. C. P., Aubin-Horth, N., and Hofmann, H. A. (2008). Fish and chips: functional genomics of social plasticity in an African cichlid fish. *Journal of Experimental Biology*, 211(18):3041–3056.

Renn, S. C. P., Carleton, J. B., Magee, H., Nguyen, M. L. T., and Tanner, A. C. W. (2009). Maternal care and altered social phenotype in a recently collected stock of Astatotilapia burtoni cichlid fish. *Integrative and Comparative Biology*, 49(6):660–673.

Repetti, R. L., Taylor, S. E., and Seeman, T. E. (2002). Risky families: family social environments and the mental and physical health of offspring. *Psychological Bulletin*, 128(2):330–366.

Sagawa, C. and Nakayasu, S. (2015). *The Collected Poems of Chika Sagawa*. Canarium Books.

Said, N., Lakehayli, S., El Khachibi, M., El Ouahli, M., Nadifi, S., Hakkou, F., and Tazi, A. (2015). Prenatal stress induces vulnerability to nicotine addiction and alters D2 receptors' expression in the nucleus accumbens in adult rats. *Neuroscience*, 304:279–285.

Saif, Z., Hodyl, N., Stark, M., Fuller, P., Cole, T., Lu, N., and Clifton, V. (2015). Expression of eight glucocorticoid receptor isoforms in the human preterm placenta vary with fetal sex and birthweight. *Placenta*, 36(7):723–730.

Salas, C., Broglio, C., Durán, E., Gómez, A., Ocaña, F. M., Jiménez-Moya, F., and Rodríguez, F. (2006). Neuropsychology of Learning and Memory in Teleost Fish. *Zebrafish*, 3(2):157–171.

Samarasinghe, R. A., Di Maio, R., Volonte, D., Galbiati, F., Lewis, M., Romero, G., and DeFranco, D. B. (2011). Nongenomic glucocorticoid receptor action regulates gap junction intercellular communication and neural progenitor cell proliferation. *Proceedings of the National Academy of Sciences*, 108(40):16657–16662.

Sapolsky, R. M. (2017). *Behave : the biology of humans at our best and worst*.

Sapolsky, R. M., Romero, L. M., and Munck, A. U. (2000). How do glucocorticoids influence stress responses? Integrating permissive, suppressive, stimulatory, and preparative actions. *Endocrine Reviews*, 21(1):55–89.

Sasaki, J. Y. and Kim, H. S. (2017). Nature, Nurture, and Their Interplay: A Review of Cultural Neuroscience. *Journal of Cross-Cultural Psychology*, 48(1):4–22.

Sengupta, P. (2013). The Laboratory Rat: Relating Its Age With Human's. *International Journal of Preventive Medicine*, 4(6):624–630.

Sofiabadi, M., Esmaeili, M.-H., Haghdoost-Yazdi, H., Dezfulian, M., Afshari, Z. H., and Goodarzvand Chegini, K. (2018). Effects of Prenatal Combined Stress on Passive Avoidance Learning and Memory in Rats. *Neurophysiology*, 50(2):116–123.

Solomon-Lane, T. K. and Hofmann, H. A. (2018). Early-life social environment alters juvenile behavior and neuroendocrine function in a highly social cichlid fish:. *bioRxiv*.

Spiers, J. G., Chen, H.-J. C., Sernia, C., and Lavidis, N. A. (2015). Activation of the hypothalamic-pituitary-adrenal stress axis induces cellular oxidative stress. *Frontiers in Neuroscience*, 8.

Sun, H., Wu, H., Liu, J., Wen, J., Zhu, Z., and Li, H. (2017). Prenatal Stress Impairs Spatial Learning and Memory Associated with Lower mRNA Level of the CAMKII and CREB in the Adult Female Rat Hippocampus. *Neurochemical Research*, 42(5):1496–1503.

Taborsky, B., Tschirren, L., Meunier, C., and Aubin-Horth, N. (2012). Stable reprogramming of brain transcription profiles by the early social environment in a cooperatively breeding fish. *Proceedings of the Royal Society B: Biological Sciences*, 280(1753):20122605–20122605.

Takahashi, A., Flanigan, M. E., McEwen, B. S., and Russo, S. J. (2018). Aggression, Social Stress, and the Immune System in Humans and Animal Models. *Frontiers in Behavioral Neuroscience*, 12.

Tinbergen, N. (1963). On aims and methods of Ethology. *Zeitschrift für Tierpsychologie*, 20(4):410–433.

Turecki, G. and Meaney, M. J. (2016). Effects of the Social Environment and Stress on Glucocorticoid Receptor Gene Methylation: A Systematic Review. *Biological Psychiatry*, 79(2):87–96.

Vallée, M., MacCari, S., Dellu, F., Simon, H., Le Moal, M., and Mayo, W. (1999). Long-term effects of prenatal stress and postnatal handling on age-related glucocorticoid secretion and cognitive performance: a longitudinal study in the rat. *The European Journal of Neuroscience*, 11(8):2906–2916.

van Bodegom, M., Homberg, J. R., and Henckens, M. J. A. G. (2017). Modulation of the Hypothalamic-Pituitary-Adrenal Axis by Early Life Stress Exposure. *Frontiers in Cellular Neuroscience*, 11.

Vey, L. T., Rosa, H. Z., Barcelos, R. C. S., Segat, H. J., Metz, V. G., Dias, V. T., Duarte, T., Duarte, M. M., and Burger, M. E. (2016). Stress during the gestational period modifies pups' emotionality parameters and favors preference for morphine in adolescent rats. *Behavioural Brain Research*, 296:408–417.

Watson, J. D. and Crick, F. H. (1953). Molecular structure of nucleic acids; a structure for deoxyribose nucleic acid. *Nature*, 171(4356):737–738.

Weaver, I. C. G., Cervoni, N., Champagne, F. A., D'Alessio, A. C., Sharma, S., Seckl, J. R., Dymov, S., Szyf, M., and Meaney, M. J. (2004). Epigenetic programming by maternal behavior. *Nature Neuroscience*, 7(8):847–854.

Weinstock, M. (2017). Prenatal stressors in rodents: Effects on behavior. *Neurobiology of Stress*, 6:3–13.

Yamamoto, N. (2009). Studies on the teleost brain morphology in search of the origin of cognition: Teleost brain morphology. *Japanese Psychological Research*, 51(3):154–167.

Zhang, T.-Y. and Meaney, M. J. (2010). Epigenetics and the Environmental Regulation of the Genome and Its Function. *Annual Review of Psychology*, 61(1):439–466.