

DNA methylation patterns in the round goby hypothalamus support an on-the-spot decision scenario for territorial behaviour

Vincent Somerville ¹, Michaela Schwaiger ¹, Philipp E. Hirsch ¹, Jean-Claude Walser ², Karen Bussmann ¹, Isabelle C. Gebhardt ³, Alexandra Weyrich ⁴, Patricia Burkhardt-Holm ¹ and Irene Adrian-Kalchhauser ^{1,*}

¹ Program Man-Society-Environment, Department of Environmental Sciences, University of Basel, Vesalgasse 1, CH-4051 Basel, Switzerland;

² Genetic Diversity Centre Zurich, ETH Zurich, Universitätsstrasse 16, CH-8092 Zurich, Switzerland;

³ Department of Comparative Neuroanatomy, University of Bonn, Institute of Zoology, Meckenheimer Allee 169, 53115 Bonn, Germany;

⁴ Leibniz Institute for Zoo and Wildlife Research (IZW), Department of Evolutionary Genetics, Alfred-Kowalke-Str. 17, D-10315 Berlin, Germany;

Abstract: How early life experiences are stored on a molecular level and affect behavioural phenotypes later in life is not well understood. In fish, reproductive phenotypes are often easily discernible and frequently depend on previous life experiences. DNA methylation is an epigenetic mechanism which is both sensitive to environmental conditions and stable across cell divisions. In this study, we therefore investigate whether DNA methylation mediates early life experiences and predetermines the territorial male reproductive phenotype in the round goby, *Neogobius melanostomus*. We investigate early life predisposition by growth back-calculations and then study DNA methylation by MBD-Seq in the round goby hypothalamus as the brain region controlling vertebrate reproductive behaviour. We find that the territorial reproductive phenotype is linked to a high growth rate in the first year of life. Hypothalamic DNA methylation patterns, however, reflect the current behavioural status independently of early life experiences. Together, our data suggest a non-predetermination scenario in which indeterminate males progress to a non-territorial status in the spawning season, and in which some males then assume a specialized territorial phenotype if current conditions are favourable.

Keywords: *Neogobius melanostomus*, reproductive strategy, epigenetic mechanisms, brain, latent effects

1. Introduction

Life experiences influence the fitness of animals by shaping traits like survival, growth rate, or fecundity [1]. Behaviour is also influenced by life experiences. In fish, dispersal and migration [2, 3] or appropriate response to predators [4, 5] are known to depend on conditions during early life stages. Additionally, reproductive behaviour is an essential character shaped by experience. For example, the outcome of competitive or of mating interactions is not only shaped by immediate cues (such as the size of the opponent or the attractiveness of the mate), but also by early life experiences of food availability, predator pressure, social status or adverse experiences [6, 7]. However, how such early life experiences are stored on a molecular level and later translated into gene expression patterns and behavioural phenotypes is not well understood.

The presence of alternative behavioural phenotypes within a single species as well as the observation of predisposition by early life experiences suggest a role for epigenetic mechanisms in the storage of early life experiences and the translation into a behavioural phenotype [8]. Epigenetic mechanisms are known to mediate plasticity [9] because they respond to environmental changes without affecting the DNA sequence, and regulate gene expression [10, 11].

The best studied epigenetic mechanism is DNA methylation. DNA methylation has been shown to respond to temperature in wild vertebrates [12], numerous environmental factors in plants [13] and larval nutrition in bees [14]. DNA methylation at promoters [15], enhancer elements and in gene bodies [16] can regulate gene expression. Importantly, DNA methylation can be stable over mitotic cell cycles and is known to mediate cellular memory [17]. Indeed, DNA methylation patterns correlate with behavioural outcomes after early life stress in humans and rodents [18, 19], or after toxicant exposure in zebrafish [20]. Thus, DNA methylation acquired earlier in life may, for example, silence a behaviour-relevant gene and thus predispose the animal for a certain behavioural phenotype later in life. Indeed, earlier studies in Atlantic salmon have highlighted the potential role of DNA methylation as the mediator between environment and reproductive phenotype [21]. However, our understanding of the role of DNA methylation patterns in predisposing individuals for the expression of certain phenotypes is limited. In particular, studies which assess whether DNA methylation patterns predict an animal phenotype prior to its manifestation are still missing.

Reproductive behaviours are usually associated with certain easily discernible phenotypes, which makes them an excellent model to study associated epigenetic mechanisms. Fish in particular display a great variety of reproductive phenotypes [22-24], such as external versus internal fertilization, paternal versus maternal brood care, or one-to-one pairings versus broadcast spawning in aggregations or hermaphroditism [23, 25, 26]. Fish reproductive phenotypes often entail characteristic colours and/or morphologies which are easy to detect. They are therefore among the best-studied experimental models within behavioural biology [27] and have been investigated in detail in many fish species [26, 28, 29]. Males in particular often adopt a territorial or a non-territorial phenotype. Typically, territorial or “bourgeois” males monopolize and defend resources such as nesting opportunities, court for females and provide brood care. Non-territorial males occasionally adopt a parasitic or sneaker life style [28, 29]. Sneaker males do not invest in territories nor build nests, and instead may try to steal fertilization by mimicking females and/or releasing sperm during the mating of a spawning couple [28, 30]. Most often, fish male reproductive phenotypes are conditional, i.e. dependent on life history events or ecological factors [31]. Prominent examples for alternative reproductive phenotypes are described within the families Gobiidae, Cichlidae, Centrarchidae, Salmonidae and Labridae [28, 29]. In recent years, some of these male reproductive phenotypes have been associated with molecular phenotypes. Several studies report differential gene expression between brains of dominant and subordinate males, or reproductive and pre-spawning males, for example in salmon [32], peacock blenny [8], cichlids [33, 34], ocellated wrasse [35, 36], bluegill sunfish [37], black-faced blenny [38], and bluehead wrasse [39].

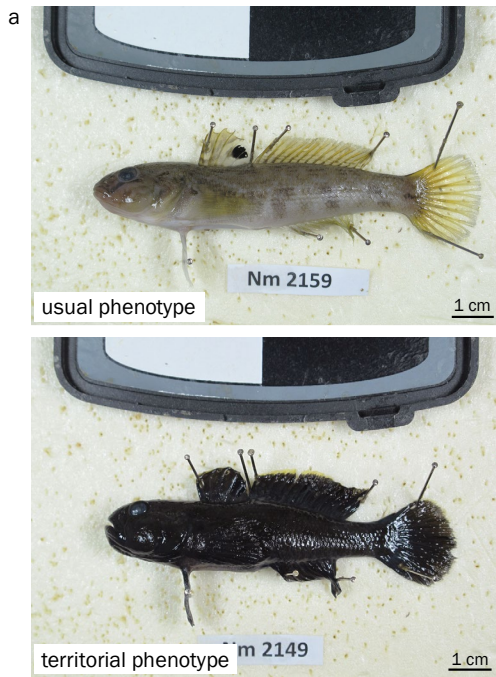
The round goby *Neogobius melanostomus* displays no major inter- or intra-sexual dimorphism outside the mating season. During the mating season, however, some males display a pale, inconspicuous colouring and do not guard nests (Figure 1a), while others undergo morphological changes and develop an intense black body pigmentation and puffy cheeks (Figure 1a) [40, 41]. The black-colored males occupy a nest, court females, and guard the eggs after oviposition [41]. Bleeker et al. (2017) [40] described morphological differences in size, gonado-somatic index and other morphological features between putative sneaker males and territorial males, with few intermediates present in the population. This may indicate that the round goby mating phenotype is determined before the first breeding season, and does not depend on current conditions. At the same time, Bleeker et al. (2017) [40] suggest that all males above a size threshold of 9.35 cm have the potential to eventually

become territorial at some point during mating season, provided nesting sites are available. Indeterminate males above the threshold are most likely capable, but not bound to becoming a nestholder. This may indicate that the round goby mating phenotype is induced by context (nest availability, male-male competition) and thus depends on current conditions. A conditional tactic for males of intermediate size is common in other goby species such as black goby, sand goby or grass goby [42-44]. Importantly, the study of epigenetic marks requires an assembled genome, which is available for the round goby (I. Adrian-Kalchhauser, publication in preparation). The round goby is therefore an excellent model to study the role of epigenetics in the establishment of reproductive phenotypes.

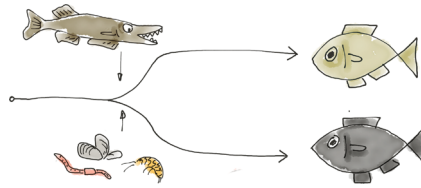
To investigate a link between DNA methylation as a molecular mechanism regulating reproductive phenotype and the phenotype itself, investigations must focus on the functional organ controlling the phenotype. In the vertebrate brain, the hypothalamus regulates many aspects of male reproductive phenotypes [45]. It intersects the neuronal and the endocrinological networks, and controls gonad development and social aspects of reproduction through the hypothalamus-pituitary-gonad axis [46]. Inputs from sensory organs are received and integrated by the inferior hypothalamic lobes. Sexual maturation and the expression of reproductive phenotypes is then mediated by steroid hormones produced and released in the hypothalamus [36]. For example, gonadotropin releasing hormone [47], arginine vasotocin as the major regulator of social reproductive behaviour [48] KiSS peptides as triggers for GnRH release [46], and brain aromatase [49] are produced in the hypothalamus.

In this paper, we investigate DNA methylation as a mechanism potentially responding to early life experiences and regulating reproductive phenotypes in the adult round goby. We first confirm that round goby reproductive phenotypes could potentially be predisposed using growth back-calculations in territorial and non-territorial males. We then map round goby brain regions by 3D reconstruction to confirm the location of the hypothalamus. Finally, we analyse DNA methylation patterns in the inferior lobes of the hypothalamus and hypothesize (1) a predetermination scenario, where early life experiences would be epigenetically imprinted, or (2) an on-the-spot decision scenario, where indeterminate males with baseline DNA methylation patterns would adopt a territorial phenotype only if conditions are favourable (Figure 1b). We sample phenotypically indeterminate males before the spawning season, and phenotypically territorial and non-territorial males during the spawning season.

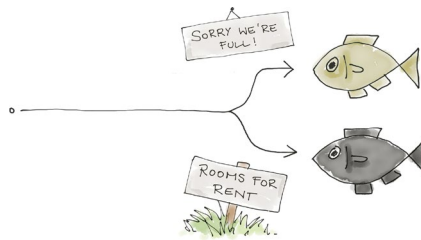
Then, we identify territorial-like DNA methylation patterns and investigate whether they are present in the hypothalamus before the expression of the territorial phenotype. We assume that an appearance of territorial methylation patterns in indeterminate males caught before spawning season would suggest predetermination, while an appearance of territorial methylation patterns only upon overt phenotype expression would suggest a conditional determination by current conditions (Figure 1c). In other words, if phenotypically indeterminate males exhibit territorial-like DNA methylation patterns, predetermination of territorial behaviour is more likely. If phenotypically indeterminate males do not exhibit territorial-like DNA methylation patterns, an on-the-spot scenario is more likely. Finally, to compare our DNA methylation data to available gene expression data from other fish species, we analyse promotor DNA methylation at the orthologs of genes that are differentially expressed between male reproductive phenotypes in other fish species.



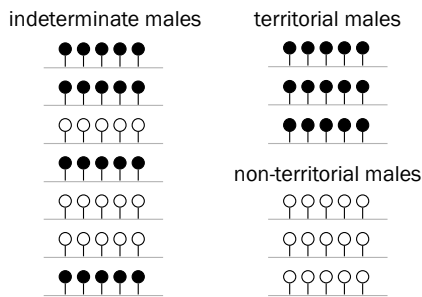
b **Scenario 1**
The territorial phenotype depends on early life events (for example food availability or predatory pressure).



Scenario 2
The territorial phenotype depends on current conditions (for example availability of nesting sites).



c **Predetermination scenario**



●●●●● region with methylated CpGs ○○○○○ region with unmethylated CpGs

Condition-dependent scenario

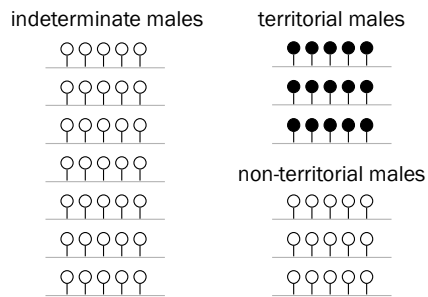


Figure 1. The territorial phenotype in round goby. a. Usually, round goby males (and females) are light brown or grey (top panel). In the spawning season, territorial males develop a black colouration (bottom panel). b. The territorial phenotype may be predetermined by early life conditions such as predation or food availability (Scenario 1). Alternatively, the territorial phenotype may be induced by current conditions such as nest availability (Scenario 2). c. DNA methylation patterns at an exemplary region for a predetermination scenario (left) and a condition dependent scenario (right). Balls on sticks represent methylated (black) or unmethylated (white) cytosines.

2. Materials and Methods

2.1. Growth in first year and luminosity

To investigate whether the territorial phenotype in the round goby could potentially be predisposed, we related growth rate in first year to body pigmentation in 113 males. Body pigmentation in fish is often controlled through endocrine pathways [50, 51], and body pigmentation expressed as luminosity is a commonly used proxy for reproductive status in male round goby [40, 41] (Figure 1a).

Males were sampled by hand netting and with fykenets in the Bay of Gdansk in Poland in the spring of 2009 (Table S1). Individuals were frozen after catch and later thawed prior to digital photography. To determine luminosity, each individual was photographed on its left side next to a grayscale for calibration. Relative luminosity was measured using Photoshop Elements 9. To obtain an intuitive value for luminosity between 0 and 1 and to include both the white and black ends of the colour spectrum into this value, the luminosity was expressed as $=1-(1/(White-Black)*(Fish-Black))$. To determine growth in early life, operculum bones were analysed. Each individual's body length was measured as total length from the tip of the snout to the end of the caudal fin. The operculum bone was removed, boiled in water and cleaned for age and growth measurements. Age of each individual was measured by counting the winter bands on the opercula bone. The size of each individual in the first and second year of their lives was then calculated according to Bagenal and Teasch (1978) [52] using the equation: $Fish(i) = \frac{Y * L(Oi) * (L(F) - Y)}{L(OT)}$, where $L(Oi)$ is the length from the tip of the opercula to the i -th winter band, $L(OT)$ is the total length of the opercula, $L(F)$ is the length of the fish and Y is the y -intercept of the equation for the linear regression between $L(OT)$ and $L(F)$. Size at age one was then subtracted from the size at age two to acquire the growth in the first year. We used a Spearman's R ranks test to detect a relationship between a trait value of early life (growth) and of adult life (pigmentation as a proxy for reproductive behaviour).

2.2. Brain morphology

To identify the hypothalamus, we reconstructed the morphology of the round goby brain (Figure S3). The brain of several adult males was exposed by dorsally opening the skull. The individuals were

then immersed in 30 ml 4% formaline in 0.1 M phosphate buffer (Stock solution 0.5 M, pH 7.4: 54.5 g Na_2HPO_4 (anhydrous), 16 g NaH_2PO_4 (anhydrous), 1000 ml distilled water). The fixative was exchanged once on the following day. A few days later, the individuals were transferred to PBS for sample shipping to the University of Bonn, where fixed brains were stained, sectioned and imaged. To this end, brains were removed from the cranial cavity and stained with 0.5 % cresyl violet containing 0.01 % Triton X-100 for 5.5 h. They were then dehydrated in an ascending ethanol series (50 %, 70 %, 80 %, 96 %, each for 1 h). Embedding in methacrylate was done in three steps using the Technovit 7100 Kombipack (Kulzer GmbH, Germany). After pre-infiltration for 3 h in a 1:1 mixture of 96 % EtOH and Technovit 7100 and overnight incubation in the infiltration solution (100 ml Technovit 7100 + 1 g Hardener I), the brains were embedded with 15 ml infiltration solution + 1 ml Hardener II. One brain was then cut in caudal-frontal orientation into transverse sections at a thickness of 5 μm on a self-constructed microtome. This microtome allows automatic cutting and digitalisation of samples with the help of an attached camera (iDS Imaging Development Systems GmbH) which takes images of the block face as sections are removed (USCHI; Ultimate Section Cutting Histology Instrument, Prof. Hofmann, Department of Comparative Neuroanatomy, University of Bonn; publication in preparation). The brain was then reconstructed by automatically aligning stained brain structures between sections in Animal Explorer 2.0 (self-written software, Prof. Hofmann, Department of Comparative Neuroanatomy, University of Bonn, publication in preparation).

2.3. Sampling of males for methylated DNA analysis

Indeterminate, non-territorial, and territorial males were caught in the harbour of Kleinhuenigen, Basel, Switzerland (47°35'14.8"N 7°35'36.2"E, see Figure S1 for map) and processed according to the workflow depicted in Figure 2. Indeterminate males were caught before the reproductive season (between 21st of March and 24th of March 2016) with minnow traps (Figure S2). Territorial and non-territorial males were caught within the reproductive season (between 17th of May and 6th of June 2016) with spawning traps (Figure S2) as described in Hirsch *et al.*, 2016 [53] and with minnow traps. The use of different traps accounts for the different behaviours of territorial and non-territorial males. Non-territorial males actively forage for food and only occasionally seek shelter. Territorial males guard and defend a nest, which they do not leave until the eggs have hatched. Therefore, minnow traps catch exclusively non-territorial males, while spawning traps catch mostly black territorial spawning males.

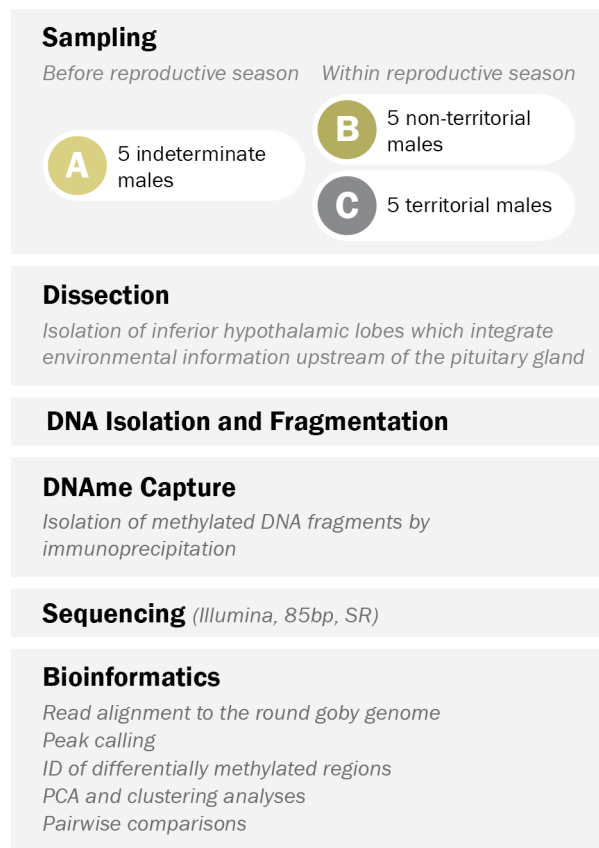


Figure 2. *Experimental setup. Indeterminate males were sampled before the reproductive season, while males with non-territorial and territorial phenotype were sampled within the reproductive season. DNA methylation patterns in the inferior hypothalamic lobes were analysed according to the outlined procedure.*

All fish were caught from a sampling depth of 3 - 4 m with permission GS 18-07-01 from the environmental department Basel-Stadt and permission 1022H from the animal welfare committee Basel-Stadt. Care was taken to pick similar-sized individuals with the aim to minimize confounding noise introduced by different ages. Average total lengths \pm standard deviation were 10.54 ± 0.45 cm for indeterminate males, 10.22 ± 0.23 cm for non-territorial males, and 10.5 ± 0.29 cm for territorial males (not significantly different according to pairwise t-tests). This is a size range in which all males have the potential to perform territorial behaviour [40] (see introduction). We determined age by scale analyses according to Grul'a *et al.*, 2012 [54], and found that all animals were between 2 and 3 years old. Animals were anaesthetised after catch with clove oil (conc. 40 mg/l in a 1:10 EtOH-dilution) according to best

practise regulation from the local fishery authority, transported to the laboratory, and frozen at -80° until further processing.

2.4. Brain dissection

To isolate the inferior hypothalamic lobes, males were thawed on ice. The brains were exposed by removing the dorsal head tissue and the skull bones, followed by severing of the optical nerves and the spinal cord. The brains were removed from the skull and placed ventral side up on a plastic container on wet ice. Under a stereo microscope, the hypothalamus was dissected, placed in a chilled FastPrep Lysing Matrix A tube (#116910050, MP Biomedicals) containing 400 mg of beads, flash frozen in liquid nitrogen and stored at -80 °C. A step by step documentation of the dissection procedure is provided in the Supplementary Files (Figure S3).

2.5. Confirmation of DNA methylation

Since DNA methylation has not been assessed in the round goby before, we next confirmed the presence of DNA methylation using experimental and bioinformatic approaches. For experimental confirmation, we digested genomic DNA isolated from round goby muscle tissue with two isoschizomeric restriction enzymes with different sensitivity to methylation (Figure S4). Hpa II and Msp I both recognise and cleave the sequence C/CGG. However, Hpa II is sensitive to CpG methylation and will not cleave a methylated target sequence. Msp I is unaffected by methylation. In organisms with scarce CpG methylation, both enzymes generate low molecular weight fragments, which appear as a smear at the bottom of an agarose gel. In organisms with significant DNA methylation, Hpa II frequently cannot access its target sequence, and therefore generates fragments high molecular weight fragments which stay at the top of an agarose gel. DNA treated with the M.SssI methyltransferase is fully methylated and can be cut only by Msp I but not Hpa II, and therefore constitutes a useful control in this experiment.

For bioinformatic confirmation, we calculated the CG ratio of the round goby genome (genome sequence available from IAK on request, publication in preparation) using the EMBOSS toolkit (version 6.6.0; Olson, 2002). Methylated Cytosines have a propensity for C to T mutation by deamination. Therefore, genomes of organisms that methylate their DNA contain less CG dinucleotides than

expected. The fruit fly does not perform genome wide DNA methylation and has a CG ratio of 0.99, while organisms such as human, zebrafish or fugu which methylate their genomes feature CG ratios of 0.2, 0.55 and 0.63, respectively [55].

2.6. DNA isolation

To isolate DNA, frozen samples were lysed by bead beating in 500 µl rat tail lysis buffer (0.1 M Tris pH 8.0, 0.2 M NaCl₂, 5 mM EDTA, 0.4 % SDS) for 20 seconds at 4 m/s on dry ice using the Fast Prep-24™ 5G (MP Biomedicals). DNA was isolated from the lysate by standard phenol/chloroform extraction and ethanol precipitation. DNA concentration, quality, and integrity were assessed with a Fragment Analyzer (Advanced Analytical Technologies).

2.7. Enrichment of methylated DNA

To enrich for methylated DNA regions, we used the MethylMiner™ Methylated DNA enrichment kit (Invitrogen) as previously described [56]. DNA samples were first sheared to a fragment size of 400 bp on a Covaris M220 Focused-ultrasonicator. Fragments smaller than 100 bp were removed using Agencourt AMPure© XP beads. Then, we immunoprecipitated methylated DNA fragments according to the manufacturer's instructions.

2.8. Library preparation and sequencing

Sequencing libraries were prepared at the Genomics Facility Basel with the KAPA Hyper Prep Kit (Kapa Biosystems) following the manufacturer's instructions. Residual adapters and adapter dimers were removed with Agencourt© AMPure© XP beads (Beckman Coulter). Finally, 15 barcoded DNA samples (from five indeterminate, five territorial and five non-territorial males) were pooled equimolarly for sequencing after quantification with the Quant-iT™ PicoGreen© dsDNA Assay Kit. The pooled sample was concentrated to 8 pM for NextSeq sequencing. Single-read sequencing was performed for 85 cycles with a NextSeq 500/550 v2 sequencing reagent kit (Illumina). Base calling and demultiplexing was performed by the Illumina Casava (1.8.2) software. We obtained $15.673.477 \pm 1.482.935$ raw reads per sample (min 13.245.959, max 17.652.564).

2.9. Read cleaning and alignment

To clean raw reads, we discarded all reads containing Illumina TruSeq adapter sequence using Cutadapt version 1.9.1 [57]. This approach was preferred over adapter clipping considering the relation of read length (86 bp) to Illumina TruSeq adapter sequences (50 bp). We then filtered for quality with prinseq version 0.20.4 [58] (minimum phred quality score ≥ 20 , no non-nucleotide sequences, CG content $\leq 20\%$ or $\geq 80\%$, no low complexity reads). In a next step we aligned the processed reads to the *N. melanostomus* reference genome (I. Adrian-Kalchhauser, publication in preparation) end-to-end with bowtie2 version 2.2.9 [59]. Mapping quality filtering (cutoff 10) and SAM to BAM and BED file conversion was done with samtools version 1.2 [60] and bedtools version 2.25.0 [61]. Of the raw reads ($15.673.477 \pm 1.482.935$), $98.18 \pm 0.56\%$ were retained after adaptor removal and quality filtering. $92.58 \pm 0.62\%$ of the trimmed and quality cleaned reads aligned to the genome.

2.10. Peak Calling

To determine methylated regions in the genome, we called peaks with MACS2 based on the reads of methylation pull-downs compared to reads of sheared but uncaptured input DNA in each sample individually. Peaks from all samples were then merged using bedtools, resulting in 334'511 peaks. The number of methylation reads in each peak and each sample was calculated using FeatureCounts, ignoring strand information and reads that had a quality score of less than 1. We then removed peaks on short and often repetitive scaffolds (less than 250 kb), thereby removing 9% of all peaks, and peaks on scaffold 364. Scaffold 364 collectively displayed extremely high differences between samples and was therefore excluded from further analyses. The most likely explanation are structural sequence elements with above / below average DNA methylation levels that differ between individuals [62]. 1% of the peaks was removed because they contained zero reads in 2 or more samples, which was likely caused by indels in individual fish.

2.11. PCA and dendrograms

We used the `prcomp` function in R to calculate a PCA on the normalized read counts (counts per million, cpm) across samples. We then filtered out 6458 peaks with very low read count by keeping only peaks that had a cpm > 1 in more than 80% of samples in at least one group (n = 156647 peaks). Finally, Voom normalization was performed to be able to identify differentially methylated peaks using Limma. To calculate dendrograms/heatmaps, we used the `heatmap.2` function in R on the normalized counts of differentially methylated BC peaks (54 peaks with $-\log_{10}$ adjusted p-value > 0.1) or on the first 6 Principal Components of the PCA of all filtered peaks (on normalized counts). Since one of the five territorial males (sample C3) behaved as an outlier in both analyses, it was excluded, and analyses were re-run without this sample. The most likely explanation is that non-hypothalamic tissue was inadvertently included during the dissection of the C3 brain.

2.12. Pairwise comparisons

To identify differentially methylated peaks, we used Limma for group comparisons, calculating fold changes and p-values, which were adjusted for multiple testing using Benjamini-Hochberg correction. Regions with below-average adjusted p-values were identified from the overall distribution of p-value versus fold change in R (Figure S6). For comparison AB, we chose the cutoff 0.01, for comparison AC, 0.1, and for comparison BC, 0.015 to single out peaks with high fold change and low p-value. Regions passing the cutoff in two contrasts were considered as overlapping for the respective phenotype.

2.13. Analysis of DNA methylation at candidate gene promoters

To compare our results with previous studies, we searched the literature on fish alternative reproductive tactics and sex determination for genes that were reported as differentially expressed in alternative reproductive morphs by quantitative PCR, microarray analysis, or transcriptome sequencing [32-39, 63-65]. Gene names were noted as reported in text, tables or figures and are listed in Table S2. To identify the corresponding genes in round goby, we first identified the zebrafish orthologue on ZFIN wherever possible and retrieved the gene symbol. Zebrafish gene symbols were not retrieved if the gene name as reported in the literature had more than three hits on ZFIN (e.g. GABA receptor alpha), or if the reported gene did not yield any hits on ZFIN (e.g. `pfkar2b`). Using Ensembl BioMart, the zebrafish gene symbols were then matched with zebrafish stable gene IDs. When one gene symbol matched two

stable gene IDs, one was arbitrarily retained. When a gene symbol could not be linked to a stable gene ID, which can happen because of a recent gene curation (for example, the gene “l1cama” was merged from two genes in 2016), the RefSeq ID of the gene was retrieved. Finally, zebrafish stable gene IDs were used to retrieve zebrafish protein sequences through Ensembl BioMart (unique records only), and zebrafish RefSeq IDs were used to retrieve zebrafish protein sequences through Batch Entrez (Table S2). Then, round goby orthologs of those zebrafish proteins were identified with Blast2GO [66].

The same approach was followed with candidate pathways and gene groups associated with alternative reproductive strategies in the literature, for example “neuronal plasticity” (Table S2). Pathways and functions reported in the literature were disregarded when they were very general (such as “catabolic process”) or when the process was much more closely related to processes other than reproduction and therefore would yield many unrelated genes (such as “skeletal system development”). Zebrafish genes associated with the respective keywords were identified on ZFIN, and processed as above to identify round goby orthologues.

To analyse DNA methylation at genes differentially expressed between fish reproductive phenotypes in other species, we determined the methylation levels (read counts determined using Feature Counts, cpm normalization as described above for peaks) at the promoters of these genes. Since promoters are not annotated in the round goby, we defined promoter regions as the proximal region 2 kb upstream the TSS [56, 67]. Using reciprocal Blast, we confirmed the round goby orthologues for the zebrafish protein sequences previously retrieved. Then we used the Limma package in R to perform a Romer analysis (a gene set enrichment analysis method based on rotation testing, which allows to perform this analysis with fewer replicates) to determine the competitive enrichment of DNA methylation at genes associated with male reproductive phenotypes.

3. Results

3.1. Early life growth rate is related to adult male phenotype

Growth rate analyses suggested that individuals which grow well in early life express a territorial phenotype later in life. We expressed growth in the first year as back-calculated size increase in mm

total length according to growth rings on opercula bones, compared it to whole body luminosity as a proxy for reproductive phenotype, and found that dark skin colouration is significantly associated with above-average growth in the first year of life (Spearman's rank test: $T=0.018$, Spearman's $R=0.22$, $p=0.018$; Figure 3). This suggests that early life experiences influence whether or not a male round goby becomes territorial as an adult.

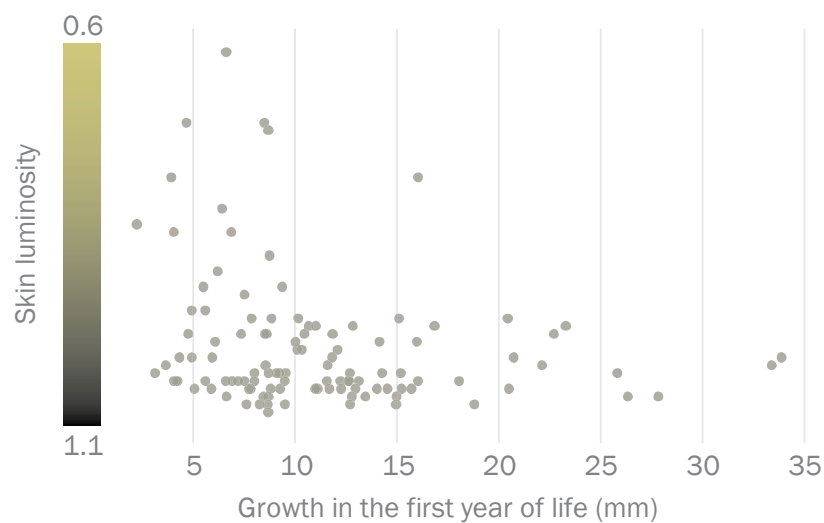


Figure 3. *Predetermination of the territorial phenotype. Males that grew better than average in their first year of life (dots towards the right side of the graph) often display a black-colored territorial phenotype in the spawning season.*

3.2. The round goby has a typical teleost brain

To reliably identify and dissect the hypothalamus, we reconstructed the round goby brain morphology. Overall, we found a typical teleost brain characterized by a large rhombencephalon, a distinct visual tectum opticum, and pronounced inferior hypothalamic lobes. 3D reconstructions identified corpus cerebelli, tectum opticum, inferior hypothalamic lobes, telencephalon, saccus vasculosus, pituitary gland, and the bulbus olfactorius of the round goby (Figure 4). The cerebellum was the most conspicuous rhombencephalic structure. The tectum opticum covered most parts of the dorsal and lateral surface in the midbrain. The diencephalic components inferior lobes and pituitary gland

dominated the ventral brain region. Measurements of the four major regions showed that the tectum opticum was the largest structure, followed by the telencephalon, the inferior lobes, and the cerebellum.

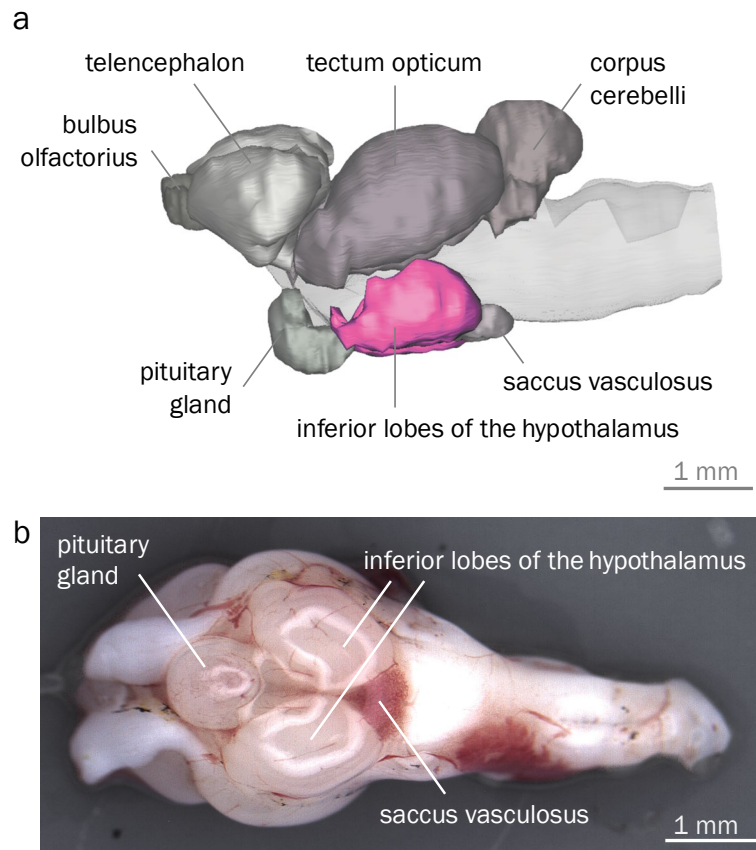


Figure 4. Round goby brain morphology. a. 3D reconstruction of a round goby brain, lateral view. Inferior hypothalamic lobes are highlighted in pink. b. Dissected round goby brain, ventral view. Anterior is to the left in both panels.

3.3. The round goby displays DNA methylation

In silico and wet lab approaches confirmed that DNA in the round goby was methylated (Figure S4). The methylation sensitive enzyme Hpa II generated larger molecular weight fragments than the methylation insensitive enzyme Msp I. Based on CG frequency calculations, the observed-to-expected CG ratio of round goby was 0.4, which is lower than the ratio expected for a non-DNA-methylating organism (1).

3.4. Territorial DNA methylation patterns arise concomitantly with the phenotype

When clustering samples based on all peaks, we found that global methylation patterns did not differ between reproductive phenotypes. Genome-wide hierarchical clustering of PCA eigenvalues derived from the entire methylome did not separate indeterminate, non-territorial, and territorial males (Figure 5a). We could, however, identify a set of differentially methylated regions (DMRs) between the different phenotypes in pairwise comparisons. When analysing only those peaks which were differentially methylated between territorial and non-territorial males, we found that 1.) non-territorial males were most similar to indeterminate males, and 2.) territorial-like DNA methylation patterns were not present in any of the indeterminate males. When clustering all samples based on regions differentially methylated between territorial and non-territorial males, indeterminate males collectively clustered with non-territorial males (Figure 5b). The results of pairwise comparisons between indeterminate, non-territorial, and territorial males supported the idea of a stepwise progression from an indeterminate to a non-territorial, and, given permissive conditions, a territorial phenotype (Figure 5c). Indeterminate males and non-territorial males differed at only 34 regions, while non-territorial and territorial males differed at 56 regions, and indeterminate and territorial males differed at 97 regions.

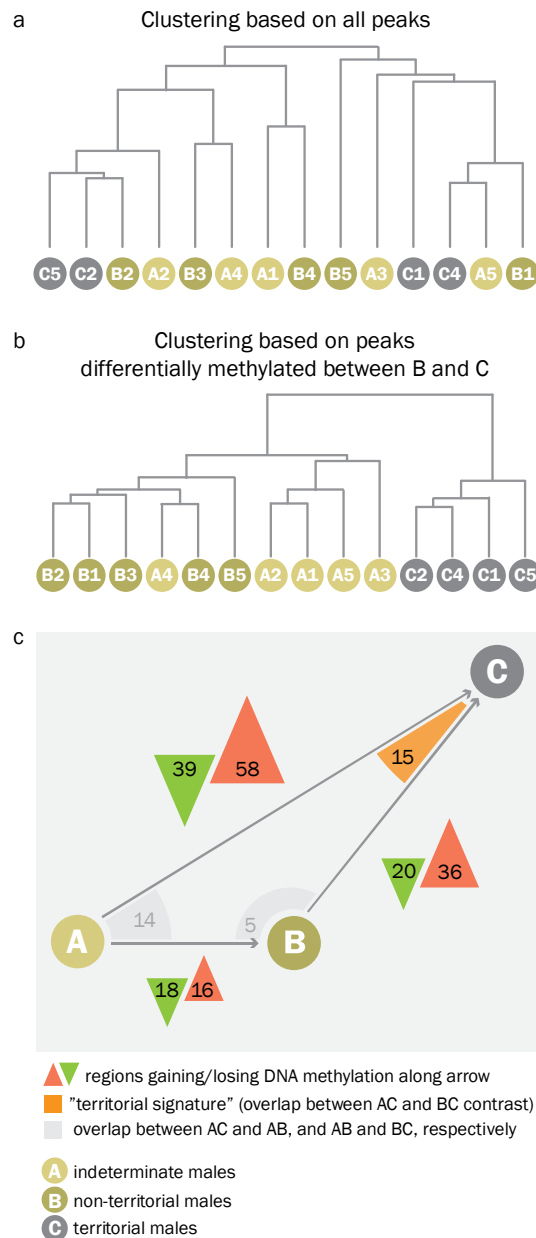


Figure 5. Indeterminate males do not display territorial DNA methylation patterns. a. Clustering based on genome wide PCA eigenvalues of all peak regions. Indeterminate, non-territorial, and territorial males are distributed randomly throughout the tree. b. Clustering based on regions differentially methylated between non-territorial and territorial males. Branches for indeterminate, non-territorial, and territorial males cluster within the respective groups. Additionally, indeterminate males cluster with non-territorial males. c. Results of pairwise comparisons. Green and red triangles represent regions that gain / lose DNA methylation during the transition represented by the grey arrow. Arrow lengths and triangle areas are scaled to represent the number of regions with differential DNA methylation. Differentially methylated regions that overlap between two comparisons are indicated by orange / grey corners.

Pairwise comparisons identified 15 regions with DNA methylation patterns that were characteristic for territorial males but not for indeterminate or non-territorial males (“territorial signature”). Using the round goby genome browser (access available from IAK on request) and the coordinates of those 15 regions, we found that these regions were frequently located in the vicinity of genes that were relevant for neuronal function and neural plasticity. For example, we identified genes associated with neuronal processes such as Tankyrase 1, sialic acid-binding Ig-like lectin, clarin 1, alkaline sphingomyelin phospho-diesterase, arachidonate 15-lipoxygenase, or neuroblast differentiation-associated protein AHNAK-like as overlapping or neighbouring genes. We also found genes potentially relevant for neuronal plasticity, such as genes implicated in signaling at membranes (star-related lipid transfer protein 8, an adhesion G-protein coupled receptor, and Guanine nucleotide exchange factor VAV2), genes regulating gene expression (THAP domain protein, several zinc finger proteins, WD repeat-containing protein 5, and bromodomain-containing protein 3), genes important for cell adhesion and extracellular matrix organisation (Tetraspanin, ADMTS-like protein, V-set and transmembrane domain containing protein, C-type mannose receptor), and genes encoding RNA regulatory proteins such as Staufen or the spliceosomal Gem-associated protein.

Finally, we investigated DNA methylation levels at the promoters of genes and gene groups that were reported as differentially expressed between alternative male reproductive phenotypes in other fish. We found that, promoter methylation at these genes and gene groups differed from promoter methylation at the average gene. According to Gene Set Enrichment analysis, promoters of genes associated with fish male reproductive phenotypes in the literature (Table S2) were significantly more often differentially methylated between the territorial and the non-territorial phenotype than the average gene (Figure 6).

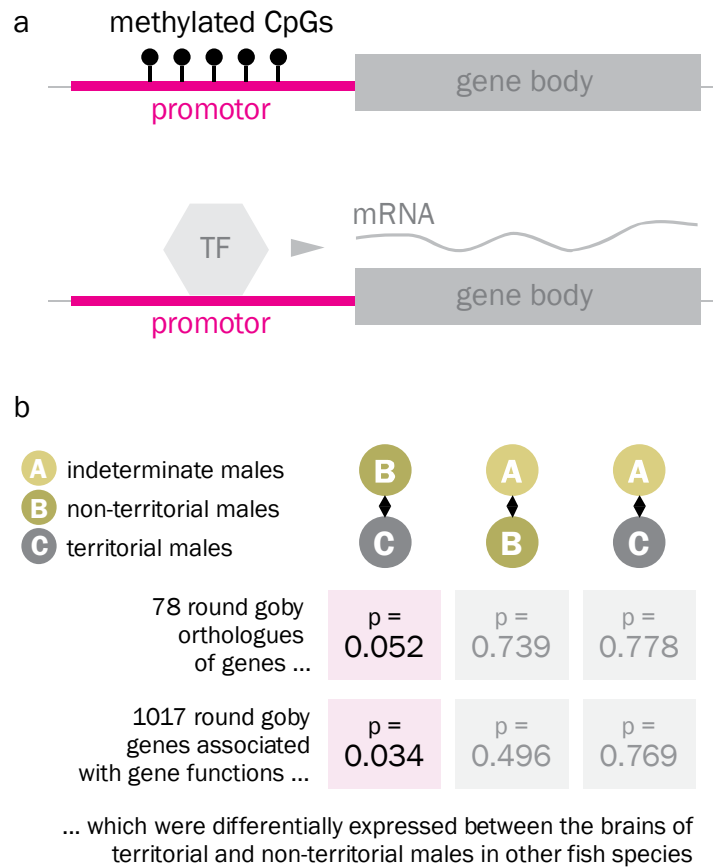


Figure 6. Promoter methylation of candidate genes. a. Promoter DNA methylation (balls on a stick) has been reported to regulate gene expression, for example by preventing transcription factors (TF) from binding to the promoter. b. According to Gene Set Enrichment analysis, promoters of candidate genes associated with reproductive phenotypes in fish in the literature (Table S2) are significantly more often differentially methylated between the territorial and the non-territorial phenotype than the average gene.

4. Discussion

In this study, we investigated whether brain DNA methylation may play a role in memorizing and translating early life experiences into a behavioural phenotype later in life in a wild fish. Specifically, we compared hypothalamic DNA methylation levels between male reproductive phenotypes in the round goby. We hypothesized that early life experiences could manifest epigenetically as DNA methylation patterns, which could then persist to adult life and predetermine reproductive phenotypes. Our alternative hypothesis was that DNA methylation patterns characteristic for a reproductive phenotype could establish at the same time as the externally visible phenotype (Figure 1b). We found that the

reproductive phenotype in the round goby was linked to growth in the first year of life. We also found a clear distinction of territorial males based on hypothalamic DNA methylation pattern from non-territorial and indeterminate males. None of the non-territorial males and indeterminate males resembled territorial males in their methylation patterns. Rather, hypothalamic DNA methylation reflected the respective current behavioural phenotype. This suggests that non-territorial males may represent an indeterminate group rather than being fixed on a non-territorial fate, and supports an on-the-spot decision scenario for the territorial phenotype (Figure 1b, Scenario 2). Below we discuss the implications of these findings in relation to current research.

Early life conditions are connected to adult reproductive phenotype

Research clearly shows that early life experiences can determine the phenotype at later developmental stages [68]. In line with these observations, our data on growth in the first year of life and later reproductive phenotype suggested a relationship between early life experiences and later reproductive life conditions in round goby. This supports the assumption that round goby reproductive phenotypes could potentially be predetermined by early life-conditions, and makes an early epigenetic setting plausible. In fish, growth rate is an essential fitness determinant [69]. Most fish show an indeterminate growth rate with limited capability of compensatory growth, and size at maturity can vary greatly. Therefore, growth rate in the first year of life is a potentially powerful predictor of later reproductive strategy: once a male is outgrown by competitors, its ability to monopolize a mating resource decreases, which may promote the adoption of a non-territorial strategy. Our growth back-calculations suggest predisposition, yet we did not find evidence for predetermination by epigenetic markers. This may be attributable to the different data sources. Growth / color data were taken in a different population than methylation data. Also, individuals from a large size-spectrum were analyzed for growth data, while the DNA-methylation study focused on a narrow size range. In the common goby *Pomatoschistus microps* or the black goby *Gobius niger*, only males at the ends of the size spectrum adopt a single phenotype, while males of medium size may act both as non-territorial and territorial males [42, 70]. By focusing on a narrow and intermediate size range, we might have excluded the extreme ends of growth rates and, thus, predetermined individuals. However, restricting age and size in the molecular data set was essential to avoid confounding the results since age related changes in DNA methylation have been described [71].

Anatomical identification of brain regions controlling reproduction

In vertebrates, the hypothalamus directs many aspects of male reproduction [45]. We therefore reconstructed round goby brain anatomy to unambiguously locate the hypothalamus. We find that the round goby displays a typical gobioid brain. Our brain map therefore enables us to reliably identify and isolate the inferior hypothalamic lobes. As is typical for gobies, the cerebellum and bulbus olfactorius are smaller, and the telencephalon larger than in other teleosts [72, 73]. Some gobioid fishes, particularly those sieving substrates for food, rely heavily on internal gustation and therefore display an enlarged vagal lobe and an accompanying dorsal expansion of the rhombencephalon [73]. The round goby feeds primarily on benthic invertebrates and lacks this feature [74]. Finally, the round goby pituitary gland is larger than in zebrafish or rainbow trout [75, 76] for reasons that are currently unknown.

The round goby is a model organism for many aspects of behaviour, such as auditory processing and communication through vocal calls [77, 78], response to odors [79], sneaking [40, 41], sex-biased movement and aggression [80, 81], or feeding [82]. These behaviours are now amenable to neuromorphological and neurophysiological investigations given that the major brain regions have been mapped in this study.

Assessment of DNA methylation across male reproductive phenotypes

The growth data suggest that the territorial reproductive phenotype may be linked to early life conditions. We found, however, no evidence for predetermination based on DNA methylation patterns. Indeterminate and non-territorial males displayed similar baseline DNA methylation before and during the spawning season, and were clearly distinct from territorial males (Figure 5b). Territorial patterns were absent from all 10 males in the dataset that did not display the territorial phenotype. This suggests that territorial-like DNA methylation in the hypothalamus develops concomitantly with the appearance of the phenotype, and that territorial DNA methylation patterns are absent before the overt onset of the phenotype. Alternatively, predetermination could depend on a few key genes involved in regulating reproductive strategy (Figure 5c). Higher sample numbers would be needed to address this.

All in all, however, our results do not show that hypothalamic DNA methylation plays a role in the long term memory of early environmental conditions. Rather, our data supports an on-the-spot decision scenario (Figure 1b, Scenario 2). This is interesting in the context of human mental health, where DNA methylation has been proposed to serve as a molecular memory mechanism altered by early life trauma and to correlate with mental health state. For example, childhood trauma and abuse induce characteristic DNA methylation patterns of the glucocorticoid receptor gene [83]. Also, DNA methylation levels at the Brain-Derived Neurotrophic factor gene are associated with Major Depressive Disorder [84]. Possibly, the round goby does store epigenetic memories of past events outside the inferior hypothalamic lobes, or using an alternative epigenetic mechanism (e.g. RNA or histone modifications).

Our data also indicate that the territorial phenotype may involve a tissue specialisation process. In pairwise comparisons with territorial males, increases in methylation levels are more common than decreases in methylation levels (Figure 4c). Depending on the genomic position, increasing methylation can both silence [15] and activate gene expression [85, 86] and is a hallmark of cellular differentiation and specialisation [87, 88]. Therefore, the territorial phenotype may potentially represent a specialisation achieved by channeling gene expression.

Finally, it is important to note that the hypothalamus contains a high diversity of neurons [89, 90]. Zones of proliferation and apoptosis have been described [91, 92], also in the context of reproduction [93]. Teleost brain plasticity may therefore have an impact on global methylation patterns in the inferior lobes. What we have identified as “territorial patterns” may reflect an increase in a certain neuronal subpopulation rather than DNA methylation changes in existing cells.

DNA methylation and invasion success

Plasticity in gene regulation has been suggested to play a role in the invasion success of round goby. Upon a temperature challenge, RNA expression levels in the round goby changed faster than in the related but less invasive tubenose goby [94]. In this context, it is interesting to note that the observed-to-expected CG ratio of the round goby is rather low (round goby: 0.4, zebrafish: 0.55, Japanese pufferfish: 0.63; [55]). Low CG ratios indicate high DNA methylation levels. Humans, for example, have particularly high levels of DNA methylation compared to other vertebrates, and their average observed-

to-expected CG ratio is 0.2 [55]. Since gene expression can be regulated through DNA methylation in promoters, enhancers, and gene bodies [15, 95], one may speculate that the impressive adaptation capacities and flexibility of the round goby (and of other invasive species) may have epigenetic underpinnings. This could be explored in a straightforward and cost-effective approach by comparing observed-to-expected CG ratios across a carefully chosen panel of invasive and non-invasive, or more and less plastic fish species.

Identification of differentially methylated genes involved in reproductive phenotypes

Previous studies identified distinct gene expression patterns associated with reproductive phenotypes in fish [32-39, 65]. Similarly, we identified DNA methylation patterns that discriminate between non-territorial and territorial males. Some of the differentially methylated regions reside within predicted genes, others reside in the vicinity of predicted genes. It is an interesting observation that many genes physically close to differentially methylated regions seem to have neuronal functions.

However, statements on functions should be taken with a grain of salt in the absence of functional data for three reasons. (1) In novel genomes, gene function is inferred solely from orthology with human genes. This process is particularly unreliable in fish considering their potential for neofunctionalization after genome duplication [96]. (2) Also, DNA methylation (as most epigenetic marks) may affect genes at a distance [97]. Physical vicinity between a methylated region and a gene is therefore not necessarily functionally significant. (3) Finally, the role of DNA methylation in fish has not been entirely clarified, and its effect on gene expression is not understood. Algorithms developed on mammals fail to identify CG islands in fish [98], and fish differ from mammals with respect to the distribution of methylated CGs in the genome [99]. Also, methylation patterns of exons and introns in zebrafish suggest that a gene's transcriptional state strongly impacts gene body methylation [100]. The observed differential methylation patterns may thus represent a consequence rather than a cause of transcriptional activity. This interpretation is in line with the observation that DNA methylation reflected current rather than past or future behavioural status.

These caveats notwithstanding, we find that genes previously found to associate with reproductive phenotypes in fish are, as a group, differentially methylated between territorial and non-territorial males

in the round goby. In the future, concomitant investigations on brain DNA methylation and brain gene expression in the same individual could help clarify the impact of DNA methylation on gene expression in the context of male reproduction. Time course analyses may help to clarify the dynamics of acquisition and erasure of epigenetic memories. We expect that a certain proportion of males in the analysed size group has previously transitioned through a reproductive phase. Yet, indeterminate and non-territorial males behaved homogeneously as a group based on hypothalamic DNA methylation data. This suggests that they either share the same reproductive history, or that they have erased methylation patterns related to the previous territorial state in the hypothalamus. Epigenetic memories may, of course, persist in other parts of the brain, or in other tissues.

5. Conclusions

In conclusion, we find that the reproductive phenotype in the round goby is linked to growth in the first year of life. However, our data indicate that the territorial phenotype in round goby is not induced by pre-existing DNA methylation patterns in the inferior hypothalamic lobes. Rather, hypothalamic DNA methylation is in line with the current phenotypic status. The methylation data suggest a stepwise progression from indeterminate male to non-territorial male to territorial male during spawning season. In this scenario, all indeterminate males progress to become non-territorial males in the spawning season. These, in turn, will specialize into territorial males if conditions are favourable.

Supplementary Materials: Supplementary Files contain 6 supplemental figures. Figure S1: Map of sampling site; Table S1: Growth and luminosity data from the Bay of Gdansk; Figure S2: Sampling equipment; Table S2: Candidate genes and candidate processes linked to alternative reproductive strategies in fish from the literature; Figure S3: Inferior lobe dissection protocol; Figure S4: Experimental confirmation of DNA methylation; Figure S5: Bioinformatic confirmation of DNA methylation; Figure S6: Volcano plots

Author Contributions: VS, PBH, AW and IAK designed the research. VS collected samples, performed dissections, and generated sequencing data. PBH and VS performed exploratory brain histology (data not shown). ICG generated 3D brain reconstructions. AW trained VS in MBD-Seq. PEH collected and analyzed fish growth and color data. VS, MS, JCW and IAK analysed sequencing data. IAK prepared the figures and the manuscript draft. VS, PEH, KB, ICG, MS, JCW, AW and PBH contributed text passages and/or critically discussed the manuscript.

Funding: This work was funded by a grant from the Freiwillige Akademische Gesellschaft Basel to Irene Adrian-Kalchhauser.

Acknowledgments: The authors are grateful to Helmut Segner for advice on hypothalamus histology and morphology, Christian Beisel from the Basel Genomics Facility for advice and guidance during sequencing, the SciCore Center of the University of Basel for providing server space and computational power and user support, and to the anonymous reviewers for evaluating the manuscript. PEH would like to thank Magnus Thorlacius, Michael Puffer and Richard Svanbäck for help with the data for the growth-luminosity relationship.

References

1. Pechenik, J.A., *Larval experience and latent effects - metamorphosis is not a new beginning*. Integrative and Comparative Biology, 2006. **46**(3): p. 323-333.
2. Kerr, L.A. and D.H. Secor, *Latent effects of early life history on partial migration for an estuarine-dependent fish*. Environmental Biology of Fishes, 2010. **89**(3-4): p. 479-492.
3. Shima, J.S. and S.E. Swearer, *The legacy of dispersal: larval experience shapes persistence later in the life of a reef fish*. Journal of Animal Ecology, 2010. **79**(6): p. 1308-1314.
4. Mirza, R.S. and D.P. Chivers, *Predator-recognition training enhances survival of brook trout: evidence from laboratory and field-enclosure studies*. Canadian Journal of Zoology, 2000. **78**(12): p. 2198-2208.
5. Mitchell, M.D., et al., *Friend or foe? The role of latent inhibition in predator and non-predator labelling by coral reef fishes*. Animal Cognition, 2011. **14**(5): p. 707-714.
6. Cunliffe, V.T., *The epigenetic impacts of social stress: how does social adversity become biologically embedded?* Epigenomics, 2016. **8**(12): p. 1653-1669.
7. Hall, S.E., et al., *A Cellular Memory of Developmental History Generates Phenotypic Diversity in C. elegans*. Current Biology, 2010. **20**(2): p. 149-155.
8. Cardoso, S.D., M.C. Teles, and R.F. Oliveira, *Neurogenomic mechanisms of social plasticity*. Journal of Experimental Biology, 2015. **218**(1): p. 140-149.
9. Jablonka, E. and G. Raz, *Transgenerational epigenetic inheritance: prevalence, mechanisms, and implications for the study of heredity and evolution*. Q Rev Biol, 2009. **84**(2): p. 131-76.
10. Szyf, M., *Epigenetics, DNA Methylation and Chromatin Modifying Drugs*. Annual Review of Pharmacology and Toxicology, 2009. **49**: p. 243-263.

11. Bird, A., *DNA methylation patterns and epigenetic memory*. Genes & Development, 2002. **16**(1): p. 6-21.
12. Weyrich, A., et al., *Paternal heat exposure causes DNA methylation and gene expression changes of Stat3 in Wild guinea pig sons*. Ecol Evol, 2016. **6**(9): p. 2657-66.
13. Richards, C.L., et al., *Ecological plant epigenetics: Evidence from model and non-model species, and the way forward*. Ecology Letters, 2017. **20**(12): p. 1576-1590.
14. Kucharski, R., et al., *Nutritional control of reproductive status in honeybees via DNA methylation*. Science, 2008. **319**(5871): p. 1827-1830.
15. Smith, Z.D. and A. Meissner, *DNA methylation: roles in mammalian development*. Nature Reviews Genetics, 2013. **14**(3): p. 204-220.
16. Potok, M.E., et al., *Reprogramming the Maternal Zebrafish Genome after Fertilization to Match the Paternal Methylation Pattern*. Cell, 2013. **153**(4): p. 759-772.
17. Law, J.A. and S.E. Jacobsen, *Establishing, maintaining and modifying DNA methylation patterns in plants and animals*. Nature Reviews Genetics, 2010. **11**(3): p. 204-220.
18. Leenen, F.A.D., C.P. Muller, and J.D. Turner, *DNA methylation: conducting the orchestra from exposure to phenotype?* Clinical Epigenetics, 2016. **8**.
19. Elliott, E., et al., *Resilience to social stress coincides with functional DNA methylation of the Crf gene in adult mice*. Nature Neuroscience, 2010. **13**(11): p. 1351-1353.
20. Knecht, A.L., et al., *Transgenerational inheritance of neurobehavioral and physiological deficits from developmental exposure to benzo[a]pyrene in zebrafish*. Toxicology and Applied Pharmacology, 2017. **329**: p. 148-157.

21. Moran, P. and A. Perez-Figueroa, *Methylation changes associated with early maturation stages in the Atlantic salmon*. BMC Genetics, 2011. **12**.
22. Breder, C.M. and D.E. Rosen, *Modes of reproduction in fishes*. Natural History Press, Natural History Press, Garden City, New York. 1966. xv, 941 pages.
23. Wootton, R.J. and C. Smith, *Reproductive biology of teleost fishes*. 2015, Oxford, Hoboken, New Jersey John Wiley & Sons, Ltd,.
24. Smith, C. and R.J. Wootton, *The remarkable reproductive diversity of teleost fishes.*, in *Fish and Fisheries*. 2016. p. 1208-1215.
25. Cole, K.S., *Reproduction and Sexuality in Marine Fishes: Patterns and Processes*. 2010: p. 432.
26. Oliveira, R.F., A.F.H. Ros, and D.M. Goncalves, *Intra-sexual variation in male reproduction in teleost fish: a comparative approach*. Hormones and Behavior, 2005. **48**(4): p. 430-439.
27. Oliveira, R.F., A.V.M. Canário, and A.F.H. Ros, *Intra-sexual variation in male reproduction in teleost fish. A comparative approach*. Hormones and behavior, 2005. **48**: p. 430–439.
28. Taborsky, M., *Sneakers, satellites, and helpers: Parasitic and cooperative behavior in fish reproduction*. Advances in the Study of Behavior, 1994. **23**: p. 1–100.
29. Taborsky, M., *Alternative reproductive tactics in fish.* , in *Alternative reproductive tactics: An integrative approach*, R.F. Oliveira, M. Taborsky, and H.J. Brockmann, Editors. 2008, Cambridge University Press.
30. Taborsky, M., *The evolution of bourgeois, parasitic, and cooperative reproductive behaviors in fishes*. J Hered, 2001. **92**(2): p. 100-110.
31. Gross, M.R., *Alternative reproductive strategies and tactics: diversity within sexes*. Trends Ecol Evol, 1996. **11**(2): p. 92-8.

32. Aubin-Horth, N., et al., *Alternative life histories shape brain gene expression profiles in males of the same population*. Proc Biol Sci, 2005. **272**(1573): p. 1655-62.
33. Maruska, K.P., et al., *Social Opportunity Causes Rapid Transcriptional Changes in the Social Behaviour Network of the Brain in an African Cichlid Fish*. Journal of Neuroendocrinology, 2013. **25**(2): p. 145-157.
34. Renn, S.C.P., N. Aubin-Horth, and H.A. Hofmann, *Fish and chips: functional genomics of social plasticity in an African cichlid fish*. Journal of Experimental Biology, 2008. **211**(18): p. 3041-3056.
35. Nugent, B.M., et al., *Neuroendocrine profiles associated with discrete behavioural variation in *Symphodus ocellatus*, a species with male alternative reproductive tactics*. Molecular Ecology, 2016. **25**(20): p. 5212-5227.
36. Stiver, K.A., et al., *Neural Gene Expression Profiles and Androgen Levels Underlie Alternative Reproductive Tactics in the Ocellated Wrasse, *Symphodus ocellatus**. Ethology, 2015. **121**(2): p. 152-167.
37. Partridge, C.G., et al., *Brain Transcriptional Profiles of Male Alternative Reproductive Tactics and Females in Bluegill Sunfish*. Plos One, 2016. **11**(12).
38. Schunter, C., et al., *Transcriptome analyses and differential gene expression in a non-model fish species with alternative mating tactics*. BMC Genomics, 2014. **15**.
39. Todd, E.V., et al., *Female Mimicry by Sneaker Males Has a Transcriptomic Signature in Both the Brain and the Gonad in a Sex-Changing Fish*. Molecular Biology and Evolution, 2018. **35**(1): p. 225-241.
40. Bleeker, K., et al., *Evidence for ontogenetically and morphologically distinct alternative reproductive tactics in the invasive Round Goby *Neogobius melanostomus**. Plos One, 2017. **12**(4).

41. Marentette, J.R., et al., *Multiple male reproductive morphs in the invasive round goby (*Apollonia melanostoma*)*. Journal of Great Lakes Research, 2009. **35**(2): p. 302-308.
42. Mazzoldi, C. and M.B. Rasotto, *Alternative male mating tactics in *Gobius niger**. Journal of Fish Biology, 2002. **61**(1): p. 157-172.
43. Scaggiante, M., et al., *Changes along the male reproductive axis in response to social context in a gonochoristic gobiid, *Zosterisessor ophiocephalus* (Teleostei, Gobiidae), with alternative mating tactics*. Hormones and Behavior, 2004. **46**(5): p. 607-617.
44. Takegaki, T., O. Svensson, and C. Kvarnemo, *Socially induced tactic change in 2 types of sand goby sneaker males*. Behavioral Ecology, 2012. **23**(4): p. 742–750.
45. Shahjahan, M., T. Kitahashi, and I.S. Parhar, *Central pathways integrating metabolism and reproduction in teleosts*. Frontiers in Endocrinology, 2014. **5**.
46. Zohar, Y., et al., *Neuroendocrinology of reproduction in teleost fish*. General and Comparative Endocrinology, 2010. **165**(3): p. 438-455.
47. Gore, A.C., *GnRH: The Master Molecule of Reproduction*. 2002: Springer US.
48. Greenwood, A.K., et al., *Expression of arginine vasotocin in distinct preoptic regions is associated with dominant and subordinate behaviour in an African cichlid fish*. Proc Biol Sci, 2008. **275**(1649): p. 2393-402.
49. Goncalves, D., et al., *Brain and gonadal aromatase activity and steroid hormone levels in female and polymorphic males of the peacock blenny *Salaria pavo**. Hormones and Behavior, 2008. **54**(5): p. 717-725.
50. Abbott, F.S., *Endocrine Regulation of Pigmentation in Fish*. American Zoologist, 1973. **73**(3): p. 885-894.

51. Leclercq, E., J.F. Taylor, and H. Migaud, *Morphological skin colour changes in teleosts*. Fish and Fisheries, 2010. **11**(2): p. 159-193.
52. Bagenal, T.B. and F.W. Tesch, *Methods for assessment of fish production in fresh waters*. Age and growth, ed. T. Bagenal. 1978: Blackwell, Oxford. 101–136.
53. Hirsch, P.E., et al., *A tough egg to crack: recreational boats as vectors for invasive goby eggs and transdisciplinary management approaches*. Ecology and Evolution, 2016. **6**(3): p. 707-715.
54. Grul'a, D., et al., *Age and growth of invasive round goby Neogobius melanostomus from middle Danube*. Central European Journal of Biology, 2012. **7**(3): p. 448-459.
55. Jabbari, K. and G. Bernardi, *Cytosine methylation and CpG, TpG (CpA) and TpA frequencies*. Gene, 2004. **333**: p. 143-9.
56. Weyrich, A., et al., *Whole genome sequencing and methylome analysis of the wild guinea pig*. BMC Genomics, 2014. **15**: p. 1-12.
57. Martin, M., *Cutadapt removes adapter sequences from high-throughput sequencing reads*. EMBnet.journal, 2011. **17**(No. 1).
58. Schmieder, R. and R. Edwards, *Quality control and preprocessing of metagenomic datasets*. Bioinformatics, 2011. **27**(6): p. 863-864.
59. Langmead, B. and S.L. Salzberg, *Fast gapped-read alignment with Bowtie 2*. Nature Methods, 2012. **9**(4): p. 357-U54.
60. Li, H., et al., *The Sequence Alignment/Map format and SAMtools*. Bioinformatics, 2009. **25**(16): p. 2078-2079.
61. Quinlan, A.R. and I.M. Hall, *BEDTools: a flexible suite of utilities for comparing genomic features*. Bioinformatics, 2010. **26**(6): p. 841-842.

62. Weisenberger, D.J., et al., *Analysis of repetitive element DNA methylation by MethyLight*. *Nucleic Acids Research*, 2005. **33**(21): p. 6823-6836.
63. Wong, R.Y., M.M. McLeod, and J. Godwin, *Limited sex-biased neural gene expression patterns across strains in Zebrafish (*Danio rerio*)*. *BMC Genomics*, 2014. **15**: p. 905.
64. Martinez, P., et al., *Genetic architecture of sex determination in fish: applications to sex ratio control in aquaculture*. *Frontiers in Genetics*, 2014. **5**.
65. Cardoso, S.D., et al., *Temporal variation in brain transcriptome is associated with the expression of female mimicry as a sequential male alternative reproductive tactic in fish*. *Molecular Ecology*, 2018. **27**(3): p. 789-803.
66. Gotz, S., et al., *High-throughput functional annotation and data mining with the Blast2GO suite*. *Nucleic Acids Research*, 2008. **36**(10): p. 3420-3435.
67. Sinnett, D., et al., *Detection and characterization of DNA variants in the promoter regions of hundreds of human disease candidate genes*. *Genomics*, 2006. **87**(6): p. 704-10.
68. Krause, E.T., et al., *Early fasting is long lasting: differences in early nutritional conditions reappear under stressful conditions in adult female zebra finches*. *PLoS One*, 2009. **4**(3): p. e5015.
69. Dmitriew, C.M., *The evolution of growth trajectories: what limits growth rate?* *Biological Reviews*, 2011. **86**(1): p. 97-116.
70. Magnhagen, C., *Alternative Reproductive-Behavior in the Common Goby, *Pomatoschistus-Microps* - an Ontogenic Gradient*. *Animal Behaviour*, 1992. **44**(1): p. 182-184.
71. Maegawa, S., et al., *Widespread and tissue specific age-related DNA methylation changes in mice*. *Genome Res*, 2010. **20**(3): p. 332-40.

72. Bauchot, R., et al., *The Brain of Rhyacichthys-Aspro (Rhyacichthyidae, Gobioidae)*. Japanese Journal of Ichthyology, 1989. **36**(2): p. 260-266.
73. Kassem, M., J.M. Ridet, and R. Bauchot, *Analyse volumetrique des principales subdivisions encephaliques chez les Gobioidae (Teleosteens, Perciformes)*. Journal für Hirnforschung, 1989. **30**: p. 59–67.
74. Vasek, M., et al., *Diet of two invading gobiid species (Proterorhinus semilunaris and Neogobius melanostomus) during the breeding and hatching season: No field evidence of extensive predation on fish eggs and fry*. Limnologica, 2014. **46**: p. 31-36.
75. Wullimann, M.F., B. Rupp, and H. Reichert, *Neuroanatomy of the zebrafish brain: a topological atlas*. . 1996: Springer Birkhäuser Verlag.
76. Meek, J. and R. Nieuwenhuys, *Holosteans and teleosts*, in *The Central Nervous System of Vertebrates*. 1998, Springer, Berlin, Heidelberg.
77. Zeyl, J.N., O.P. Love, and D.M. Higgs, *Condition-dependent auditory processing in the round goby (Neogobius melanostomus): links to sex, reproductive condition and female estrogen levels*. Journal of Experimental Biology, 2013. **216**(6): p. 1075-1084.
78. Rollo, A. and D. Higgs, *Differential acoustic response specificity and directionality in the round goby, Neogobius melanostomus*. Animal Behaviour, 2008. **75**: p. 1903-1912.
79. Laframboise, A.J., et al., *The Effect of Elevated Steroids Released by Reproductive Male Round Gobies, Neogobius melanostomus, on Olfactory Responses in Females*. Journal of Chemical Ecology, 2011. **37**(3): p. 260-262.
80. Marentette, J.R., et al., *Laboratory and field evidence of sex-biased movement in the invasive round goby*. Behavioral Ecology and Sociobiology, 2011. **65**(12): p. 2239-2249.

81. Marsh-Rollo, S.E.e.a., *Is there a role for aggression in round goby invasion fronts?* Behaviour, 2012. **149**: p. 685-703.
82. Carman, S.M., et al., *Diel interactions between prey behaviour and feeding in an invasive fish, the round goby, in a North American river.* Freshwater Biology, 2006. **51**(4): p. 742-755.
83. McGowan, P.O., et al., *Epigenetic regulation of the glucocorticoid receptor in human brain associates with childhood abuse.* Nature Neuroscience, 2009. **12**(3): p. 342-348.
84. Fuchikami, M., et al., *DNA Methylation Profiles of the Brain-Derived Neurotrophic Factor (BDNF) Gene as a Potent Diagnostic Biomarker in Major Depression.* Plos One, 2011. **6**(8).
85. Hahn, M.A., et al., *Relationship between gene body DNA methylation and intragenic H3K9me3 and H3K36me3 chromatin marks.* PLoS One, 2011. **6**(4): p. e18844.
86. Jjingo, D., et al., *On the presence and role of human gene-body DNA methylation.* Oncotarget, 2012. **3**(4): p. 462-74.
87. Mohn, F., et al., *Lineage-specific polycomb targets and de novo DNA methylation define restriction and potential of neuronal progenitors.* Molecular Cell, 2008. **30**(6): p. 755-766.
88. Sheaffer, K.L., et al., *DNA methylation is required for the control of stem cell differentiation in the small intestine.* Genes & Development, 2014. **28**(6): p. 652-664.
89. Chen, R.C., et al., *Single-Cell RNA-Seq Reveals Hypothalamic Cell Diversity.* Cell Reports, 2017. **18**(13): p. 3227-3241.
90. Machluf, Y., A. Gutnick, and G. Levkowitz, *Development of the zebrafish hypothalamus.* Trends in Neuroendocrinology, 2011. **1220**: p. 93-105.
91. Kuroyanagi, Y., et al., *Proliferation zones in adult medaka (Oryzias latipes) brain.* Brain Research, 2010. **1323**: p. 33-40.

92. Puschina, E.V. and D.K. Obukhov, *Processes of Proliferation and Apoptosis in the Brain of the Amur Sturgeon*. *Neurophysiology*, 2011. **43**(4): p. 271-286.
93. Zikopoulos, B., M. Kentouri, and C.R. Dermon, *Cell genesis in the hypothalamus is associated to the sexual phase of a hermaphrodite teleost*. *Neuroreport*, 2001. **12**(11): p. 2477-2481.
94. Wellband, K.W. and D.D. Heath, *Plasticity in gene transcription explains the differential performance of two invasive fish species*. *Evolutionary Applications*, 2017. **10**(6): p. 563-576.
95. Yang, X.J., et al., *Gene Body Methylation Can Alter Gene Expression and Is a Therapeutic Target in Cancer*. *Cancer Cell*, 2014. **26**(4): p. 577-590.
96. Glasauer, S.M.K. and S.C.F. Neuhauss, *Whole-genome duplication in teleost fishes and its evolutionary consequences*. *Molecular Genetics and Genomics*, 2014. **289**(6): p. 1045-1060.
97. Stone, A., et al., *DNA methylation of oestrogen-regulated enhancers defines endocrine sensitivity in breast cancer*. *Nature Communications*, 2015. **6**.
98. Han, L. and Z.M. Zhao, *Comparative analysis of CpG islands in four fish genomes*. *Comparative and Functional Genomics*, 2008.
99. Jiang, N., et al., *Conserved and Divergent Patterns of DNA Methylation in Higher Vertebrates*. *Genome Biology and Evolution*, 2014. **6**(11): p. 2998-3014.
100. McGaughey, D.M., et al., *Genomics of CpG Methylation in Developing and Developed Zebrafish*. *G3-Genes Genomes Genetics*, 2014. **4**(5): p. 861-869.