Asymmetric robustness in the feedback control of the retinoic acid network response to environmental disturbances

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ABSTRACT

Retinoic acid (RA) is a central developmental signal whose perturbation results in teratogenic outcomes. We performed transient physiological RA signaling disturbances during embryogenesis followed by kinetic RNAseq and high-throughput qPCR analysis of the recovery. Unbiased comparative pattern analysis identified the RA network as a key differentially regulated module aimed at achieving RA signaling robustness. We analyzed this module using a principal curve-based approach determining clutch-wise variability, and organized the results into a robustness efficiency matrix comparing the shifts in RA feedback regulation and *hox* gene expression. We found that feedback autoregulation was sensitive to the direction of the RA perturbation: RA knock-down exhibited an upper response limit, whereas RA addition did not activate a feedback response below a threshold. These results suggest an asymmetric capacity for robust feedback control of RA signal during early development based on genetic polymorphisms, likely a significant contributor to the manifestation of developmental defects.

KEYWORDS

Embryo development; Retinoic acid; Xenopus embryo; time-series transcriptomics; temporal gene expression pattern analysis; developmental trajectory analysis; autoregulatory feedback control.

INTRODUCTION

Retinoic acid (RA) is one of the central regulatory signaling pathways active during vertebrate embryogenesis as well as in adult tissue homeostasis regulating the transcription of numerous downstream target genes (Campo-Paysaa et al., 2008; Clagett-Dame and DeLuca, 2002; le Maire and Bourguet, 2014; Marill et al., 2003; Mark et al., 2009; Metzler and Sandell, 2016). RA is synthesized from vitamin A (retinol) or other retinoids or carotenoids obtained from the diet (Ghyselinck and Duester, 2019; Kedishvili, 2016). During embryogenesis, changes in RA levels, signal timing or signal localization, result in severe developmental malformations arising from both abnormally low and excess RA signaling. Excessive RA signaling induces a wide array of developmental malformations including brain defects, organ malformations and additional anatomical anomalies (Clagett-Dame and Knutson, 2011; Collins and Mao, 1999; Cunningham and Duester, 2015; Marill et al., 2003; Mark et al., 2009; Shenefelt, 1972). In addition, multiple developmental and adult disorders and syndromes have been linked to attenuated RA signaling, demonstrating the importance of RA homeostasis in normal embryogenesis and disease. Syndromes linked to reduced RA signaling include vitamin A deficiency syndrome (VAD), DiGeorge/VeloCardioFacial syndrome (DG/VCF), Fetal Alcohol Spectrum Disorder (FASD), Congenital Heart Disease (CHD), neural tube defects, and multiple types of cancer (Coberly et al., 1996; El Kares et al., 2010; Hartomo et al., 2015; Kim et al., 2005; Kot-Leibovich and Fainsod, 2009; Pangilinan et al., 2014; See et al., 2008; Timoneda et al., 2018; Urbizu et al., 2013). RA levels are tightly regulated at multiple levels throughout life to prevent aberrant gene expression as a result of diet and other environmental changes. Discrete regulatory roles of RA are usually separated temporally and spatially, taking place in different tissues, embryonic regions, or cell types, which require the fine-tuned regulation of the source, the level, and the gene-regulatory response to this signal. This quantitative, spatial and temporal regulation relies in part on the regulated expression and

activity of RA biosynthetic and metabolizing enzymes including members of the cytochrome P450 family, like CYP26, that render retinoids biologically inactive (Dobbs-McAuliffe et al., 2004; Duester et al., 2003; Hollemann et al., 1998; Sakai et al., 2001).

RA biosynthesis involves two sequential oxidation steps: first, alcohol dehydrogenases (ADH) or short-chain dehydrogenase/reductases (SDR) oxidize vitamin A (retinol, ROL) to retinaldehyde (RAL), followed by the retinaldehyde dehydrogenase (RALDH) catalyzed oxidation of RAL to RA (Duester, 2008; Kedishvili, 2016; Parés et al., 2008). RA availability is further affected by ROL, RAL, and RA binding proteins (Kono and Arai, 2015; Napoli, 2017, 2016; Schroeder et al., 2008). ROL and RAL can also be produced from retinyl ester stores or from ß-carotene from food sources (Blaner, 2019; O'Byrne and Blaner, 2013). Nevertheless, in the early embryo RALDH2 (ALDH1A2) takes center stage, as its expression and availability is the earliest rate-limiting step in RA biosynthesis. In vertebrate gastrula embryos, RA signaling is triggered by the activation of *raldh2* transcription whose protein product completes the last enzymatic step in RA biosynthesis (Begemann et al., 2001; Chen et al., 2001; Grandel et al., 2002; Niederreither et al., 1999). During RA biosynthesis, substrate availability for the RALDH enzymes, RAL, is controlled by members of the SDR, ADH and AKR families (Adams et al., 2014; Billings et al., 2013; Feng et al., 2010; Porté et al., 2013; Shabtai et al., 2016; Shabtai and Fainsod, 2018). Importantly, expression of many of the enzymes involved in RA biosynthesis is spatially regulated as well, resulting in a gradient of RA activity which is highest close to the caudal end of the embryo and very restricted in the developing head (Dubey et al., 2018; Niederreither et al., 1997; Schilling et al., 2016). Additional spatial and temporal regulation of this signaling pathway is provided by regulated expression of other components, including retinoic acid receptors (RAR and RXR) and retinoid-binding proteins (Cui et al., 2003; Janesick et al., 2015; Lohnes et al., 1995; Mendelsohn et al., 1994; Xavier-Neto et al., 2015). Taken together, RA signaling is controlled through regulated biosynthesis

and degradation of the ligand as well as restricted temporal-spatial expression of the metabolic and gene-regulatory components, which together are expected to provide robustness to the RA signal homeostasis. Although the initial response to changes in the level of RA is executed by the available enzymes, regulation is achieved to a large extent by an RA-mediated transcriptional regulation of the genes encoding many of the enzymes involved in RA metabolism. This establishes an auto-regulatory feedback control framework of the RA signal. Besides the maternal nutritional status that can affect the levels of RA signaling in the developing embryo, environmental exposure to chemicals such as alcoholic beverages (ethanol) or other chemicals can affect the biosynthesis of RA or the status of this signaling pathway (Paganelli et al., 2010; Shabtai et al., 2018). These observations point to the close interaction of RA signaling and the environment and the necessity to adapt the RA signaling network to nutritional changes and insults (e.g., ethanol). This adaptation and maintenance of normal signaling levels under changing conditions is termed robustness (Eldar et al., 2004; Nijhout et al., 2019).

A better understanding of the RA signaling pathway during embryogenesis, its multiple regulatory roles, and its regulation require a deeper understanding of the signaling robustness in the presence of environmental disturbances. Very commonly, the RA pathway is studied by increasing the levels of this signal from exogenous sources (Durston et al., 1989; Kessel, 1992; Sive et al., 1990). Alternatively, loss-of-function studies take advantage of RAR inhibitors, inverse agonists, inhibitors of RA biosynthesis, or degradation of the signal (Hollemann et al., 1998; Janesick et al., 2014, 2013; Kot-Leibovich and Fainsod, 2009). Interestingly, in a number of RA loss-of-function studies, the developmental malformations observed are relatively mild suggesting the presence of a compensatory mechanism conferring some robustness to perturbations in RA signal (Blumberg et al., 1997; Hollemann et al., 1998; Janesick et al., 2014; Koide et al., 2001; Shabtai et al., 2018; Sharpe and Goldstone, 1997). Paradoxical teratogenic

outcomes were observed in a number of RA manipulation studies, suggesting the activity of regulatory feedback mechanisms (D'Aniello et al., 2013; D'Aniello and Waxman, 2015; Lee et al., 2012; Rydeen et al., 2015). The RA signaling pathway due to the nature and source of the signaling moiety is poised to respond to dietary and environmental changes. As such the RA ligand can readily be manipulated exogenously by pharmacological approaches. To further characterize the robustness of RA signaling during early embryogenesis we employed clearly defined and transient RA manipulations that were terminated during early gastrula, and the kinetics of recovery of the embryos was monitored by RNAseq for several hours thereafter. The RNAseq results uncovered high robustness to perturbations in the RA signal with relatively small transcriptome-wide changes. Interestingly, a high proportion of the genes whose expression changed in a manner that is dependent on the direction of RA manipulation encode for components of the RA metabolic and signaling network. Multiple biological repeats were analyzed, with each repeat from a single clutch of embryos for all treatments and controls. Comparative analysis of the biological repeats of the manipulation and recovery experiment revealed differences between clutches in their individual robustness to enhanced or suppressed RA signaling. These results exposed potential consequences of the underlying genetic differences between clutches as each one originated from a single female, and most *Xenopus laevis* frogs from laboratories are outbred. Our results suggest an asymmetric capacity for robust control of RA signal in the early embryo, likely contributing to the human developmental defects that arise due to imbalance (most often, a reduction) in Vitamin A levels during early development.

RESULTS

Experimental RA manipulation uncovers signaling robustness

To understand the regulatory role of RA signaling in early embryos, we routinely employ two approaches to reduce the levels of this ligand (Fig. 1A). We either suppress the oxidation of retinaldehyde to RA with RALDH inhibitors like 4-diethylaminobenzaldehyde (DEAB) (Kot-Leibovich and Fainsod, 2009; Shabtai et al., 2016; Shabtai and Fainsod, 2018), or we overexpress the RA hydroxylase, CYP26A1 (Hollemann et al., 1998; Yelin et al., 2005), that renders this signal biologically inactive (Dobbs-McAuliffe et al., 2004; Niederreither et al., 2002). Over a wide range of concentrations these treatments result in clear, but relatively mild, developmental defects for such a central regulatory signaling pathway (compare Fig. 1B with Fig. 1C, D). An efficient approach to induce severe phenotypes by RA signaling loss-of-function (LOF) is to combine knock-down treatments that target retinoid metabolism at different steps (Fig. 1A, E). These observations led us to propose that RA metabolism and signaling exhibit strong robustness in the context of experimental manipulation of RA levels.

To study the physiological robustness of retinoic acid signaling we focused on moderate perturbations of this pathway within the physiological range (about 100-150 nM all-*trans* RA) determined in *X. laevis* early embryos (Durston et al., 1989; Kraft et al., 1995; Kraft and Juchau, 1992; Sive et al., 1990). To empirically determine the RA concentrations to use, we tested the effects on gene expression of increasing concentrations (1 nM - 1 μM) spanning the physiological range (Supplemental Fig. S1). Quantitative real-time PCR (qPCR) was performed on RNA samples of treated embryos collected during early (st. 10.25) and late gastrula (st.12)(Nieuwkoop and Faber, 1967). We analyzed genes encoding enzymes involved in RA metabolism and known RA target genes during early embryogenesis. Genes positively regulated by RA at both stages, *hoxb1*, *cyp26a1*, and *dhrs3* exhibited dose-dependent responses (Supplemental Fig. S1A-C). The genes *raldh2* (*aldh1a2*) and *rdh10,* are down-regulated by

most RA doses (Supplemental Fig. S1D, F), while *raldh3* (*aldh1a3*) is up-regulated earlier on and is repressed later on by the treatment (Supplemental Fig. S1E). Importantly, RA concentrations as low as 10 nM had a significant effect on gene expression.

To study the robustness of RA signaling in early *Xenopus laevis* embryos, we established an experimental protocol where the levels of RA were transiently manipulated pharmacologically. The perturbation was terminated by several washings to remove the treatment and then the embryos were monitored post-treatment during the recovery period (Fig. 2). Embryos were treated with RA (10 nM) for 2 hours starting from late blastula (st. 9.5). During early gastrula (st. 10.25), about 2 hours after the treatment was initiated, the embryos were washed and allowed to recover. At different time points during the recovery period, samples were collected to perform kinetic analysis of the changes in gene expression by qPCR (Fig. 2). To monitor the changes in RA signaling levels by gene expression, two well-characterized RA-regulated genes, *hoxb1* and *hoxb4,* were studied. Expression analysis of both genes showed that at the time of treatment washing (t_0), both genes were upregulated when compared to control sibling embryos (Fig. 2A). Two hours into the recovery, both RA target genes were back to control expression levels when compared to untreated sibling embryos from the same clutch at the same developmental stage. To begin understanding the homeostasis of RA metabolism and the dynamic regulation of RA levels we studied the expression of *dhrs3*, which encodes an enzyme that preferentially reduces retinaldehyde to retinol, thus attenuating RA biosynthesis (Feng et al., 2010), *cyp26a1*, which targets RA for degradation, and *raldh2* (*aldh1a2*) that produces RA from retinaldehyde (Shabtai et al., 2016). As expected, both negative regulators of RA signaling, *dhrs3,* and *cyp26a1*, are upregulated by the increased RA at t_0 (Fig. 2B). Their return to normal expression levels is only observed in the 4-hour samples in contrast to the *hox* genes that returned to normal expression 2 hours earlier. As expected, *raldh2* exhibited a downregulation at t_0 promoted by excess RA (Fig. 2B). It also took over 4

hours for this gene to return to normal expression levels. These results indicate that the expression of genes encoding RA metabolic enzymes, which themselves are regulated by RA (Supplemental Fig. S1), is shifted to achieve normal RA levels in the face of external perturbation to RA levels, even though these genes remain abnormally expressed for a longer period.

A complementary study was performed by reducing RA biosynthesis taking advantage of DEAB (Fig. 2C,D). All genes studied exhibited fluctuations during the recovery period. Importantly, *hoxd1* and *hoxb1*, key targets of RA signaling, reached almost normal levels at an earlier stage than the genes encoding RA metabolic components (Fig. 2C). As expected, genes encoding anabolic enzymes, e.g., *raldh2*, were upregulated, and catabolic components, e.g., *cyp26a1*, were downregulated (Fig. 2D).

The results of the kinetic analysis of the recovery from RA manipulation by qPCR provided a novel and important insight into the robustness of RA signaling. We observed that while RA downstream target genes reach normal expression levels relatively quickly, expression of genes encoding RA metabolic enzymes is maintained at seemingly abnormal levels for a longer period of time, such that their combined abnormal activity levels likely result in almost normal RA signaling levels. From a robustness perspective, such a disturbance amelioration can be achieved by altering the activity of specific sets of pathway components, with the corresponding gene expression change signature indicative of an auto-regulatory feedback control response aimed at canceling out the disturbance(s). Such expression changes suggest the hypothesis that during early development RA signaling robustness is achieved, at least in part, via feedback control of network components. This feedback mechanism is aimed at preventing a significant differential gene expression response and the resulting teratogenic outcomes. Our qPCR results provide evidence consistent with the robustness achieved via feedback control. These observations counteract the null hypothesis that the early embryo is

largely refractory, i.e., robustness due to insensitivity, to disturbances in the RA signal. To gain a better understanding of the robustness of RA signaling and adaptation of the metabolic network to disturbances, we performed a kinetic transcriptomic analysis. In an attempt to optimize the kinetic study, parameters such as developmental stages and time between samples were empirically tested. The experimental design involves treating embryos for 2 hours from late blastula (st. 9.5) to early gastrula (st. 10.25) and collecting samples every 1.5 hours after terminating and washing the treatment (Fig. 3A). Embryos were treated with RA (10 nM) or DEAB (50 μM). For each biological repeat, all treatments, controls, and time points were collected from a single fertilization, from the eggs (clutch) of a single female. The efficiency of the treatments and quality of the RNA samples was initially ascertained by qPCR for changes in *hox* gene expression as a direct readout of the RA signal levels. Only those experiments where both treatments exhibited the expected up-regulation (RA) or down-regulation (DEAB) in *hox* gene expression were selected for RNA-seq.

Normal developmental transcriptome changes mask the effects of RA signaling perturbations

We analyzed the time series transcriptomic data set for differential expressed genes using a two-way ANOVA (t=0, 1.5, 3, 4.5 hours; treatments: RA, DEAB, control; n=6 biological replicates). Our analysis revealed a total of 4693 significantly differentially expressed genes with greater than 2-fold changes over time (compared to t=0 within each treatment group; multiple testing corrected q-value < 0.05). Principal Component Analysis (PCA) of the gene expression variation showed that all samples separated progressively along the first principal component (PC1) which corresponds to the developmental stage (Fig. 3B). Surprisingly, RA manipulated samples clustered with the control samples of the same developmental stage. Normal transcriptomic changes as a result of progression through embryogenesis appear to be the dominant variable distinguishing between the samples

irrespective of treatment (Fig. 3B). The second component (PC2) separated the sample groups at intermediate time points (1.5 and 3h) from those at 0 and 4.5h time points, indicating a transient differential expression shift as the next most dominant pattern in the data. The effect of the RA and DEAB treatments on the transcriptome was not readily apparent in the next seven principal components. The tenth principal component (PC10) showed some separation of the RA treatment group from Control and DEAB treatments (Fig. 3C), whereas the eighth principal component (PC8) showed some separation of DEAB group from RA and Control groups (not shown). The top-ranked genes along PC10 showed distinct dynamic patterns across the treatments, whereas top-ranked genes along PC1 and PC2 largely corresponded to in-common dynamic changes over time (Fig. 3D; Supplemental Fig. S2). The patterns of both opposed RA manipulations, RA and DEAB, closely resembled the control sample for the top-ranked genes along PC1 and PC2, further supporting the normal developmental changes as the dominant pattern. The overall magnitude of induced changes in gene expression in response to the RA or DEAB treatments appears to be less than the normal transcriptome changes occurring during early developmental stages, raising the possibility that RA signaling robustness dampens the gene expression changes expected from abnormal RA levels. Taken together, these results suggest that the RA and DEAB treatments, applied at moderate physiologically relevant concentrations, do not alter the transcriptome extensively in the whole embryo. These results are consistent with the response of a robust system that functions to limit the gene expression changes in the majority of the transcriptome.

Dynamic pattern analysis reveals early developmental stage-specific/dependent transcriptional patterns

In order to unmask the potential effects of RA and DEAB treatments on transcriptomic changes during early development, we analyzed the clutch-averaged data using an unbiased

dynamic pattern analysis approach to categorize the gene expression profiles along all possible discretized patterns (Kuttippurathu et al., 2016). Each pattern is based on the direction of up- or down-regulation above a 2-fold threshold (three possibilities: up-regulation, down-regulation, or no change) at each of the three recovery time points relative to the stage the treatment was terminated (early gastrula; t=0), yielding 3*3*3 = 27 possible discretized patterns. Such an exhaustive approach allows us to enumerate the dominant as well as subtle patterns in the data and overcomes limitations of conventional cluster analysis that is likely to miss or mask the smaller groups of genes with distinct expression profiles over time. In our analysis, not all possible dynamic patterns had representative genes. Out of the 27 possible dynamic patterns, only 10 patterns were exhibited by genes in the transcriptome in at least one of the three experimental groups (RA, DEAB, Control)(Fig. 4A). Of these, only 5 patterns were exhibited by a substantial number of genes (>100) in at least one of the three experimental groups. These five patterns correspond to up- or down-regulation at later time points (3h and 4.5h), and persistently induced or suppressed expression at all three recovery time points, including progressive changes in gene expression over time (Fig. 4A). At the 2-fold threshold, there were no genes that showed an initial down-regulation followed by an up-regulation and vice versa. There were no significant differences in the gene counts between RA or DEAB and control groups (two-tailed Z test, $p > 0.05$). Analysis of statistically enriched pathways and processes in the control group highlighted several functional annotations including development, cell cycle, morphogenesis, RA biosynthesis, gastrulation, and others. (Fig. 4A). These expression dynamics are consistent with the changes occurring in the early gastrula stage when the endogenous RA system is activated, as supported by the biological processes statistically enriched in the Control group (Fig. 4B). The patterns with relatively fewer genes (<100) correspond to transient up- or down-regulation at 3h that is normalized by 4.5h, as well as progressive down-regulation.

The results shown in Fig. 4 highlight two aspects of the effect of perturbations in the RA signal. First, at the 2-fold threshold, there are no dynamic patterns of gene expression changes that are specific to RA or DEAB treatment conditions. Second, the number of genes per pattern is of a similar order of magnitude between the two treatments and control. These results suggest that, at physiologically relevant concentrations employed here, RA and DEAB treatments modulate the transcriptional and post-transcriptional regulators at a scale resembling the changes in controls, albeit with differences in potential targets. For instance, only a subset of genes that showed late down-regulation (first row in Fig. 4A) were common across all the three groups (772 genes, Fig. 4C). Several genes showed similar late down-regulation between the treatments or between one of the treatments and the Control group (Fig. 4C). In addition, many genes showed a late down-regulation pattern only in one of the treatment groups or in the Control (Fig. 4C). While the Venn diagram analysis shown in Fig. 4C revealed the overlaps between the RA and DEAB treatments and Control within a given differential regulation pattern, the overlap across patterns is not immediately clear. In the next section, we pursue an exhaustive approach to analyze these overlapping gene sets.

Novel comparative pattern analysis reveals the transcriptional changes sensitive to perturbation of the RA signal

To compare the RA and DEAB groups for their effect on gene expression relative to the unperturbed temporal pattern observed in the control samples, we adapted a recently developed unbiased approach named COMPACT for analyzing time-series differential transcriptomic profiles across multiple experimental conditions (Kuttippurathu et al., 2016). In this scheme, we started with the statistically significant genes within each treatment group (two-way ANOVA; $q<0.05$), and constructed discrete patterns based on differential gene expression between RA and control groups (81 possible patterns, with up-, down- and no-

regulation at t=0, 1.5, 3 and 4.5 h). Next, we constructed similar discrete patterns for DEAB versus control groups. Only the patterns with at least one gene in either comparison were included in the subsequent analysis, yielding 32 distinct patterns (Fig. 5A). Finally, we intersected the two distributions to create a matrix of comparative patterns where each element corresponds to a distinct pair of patterns corresponding to RA vs. control and DEAB vs. control (Fig. 5B). The discrete patterns were based on a 1.3-fold average difference between RA (or DEAB) and control groups at each of the four time points. The effect size threshold was chosen at a lower level than 2-fold as the differential expression analysis revealed that RA/DEAB perturbations were leading to a smaller magnitude of changes at each time point, as compared to the larger changes occurring normally over time (Fig. 4A).

Analysis of the COMPACT matrix (Fig. 5B, Extended Data 1) demonstrates that a majority of the genes were sensitive to the RA signal in only one direction of perturbation. A total of 193 genes showed differential regulation only with the addition of exogenous RA relative to Control (middle row), whereas 224 genes were differentially responsive to inhibition of RA production by DEAB (middle column). Of the genes that showed differential regulation to both RA and DEAB perturbations, 88 genes showed up-regulation or down-regulation irrespective of RA or DEAB treatment (quadrants a and d in Fig. 5B). A set of 48 genes showed opposite transcriptional outcomes in response to exogenous RA increase versus inhibition of RA production (quadrants b and c in Fig. 5B). Interestingly, the set of genes that showed up-regulation by exogenous RA addition and down-regulation by DEAB (quadrant b) contained many genes involved in the biosynthesis and metabolism of RA (Fig. 5C).

We mapped the expression changes shown in Fig. 5B,C to the RA signaling and metabolic pathways (Fig. 5D,E). Notably, the genes encoding proteins involved in control of RA levels (*cyp26a1*, *dhrs3*) were up-regulated and the genes encoding for proteins responsible for RA production (*aldh1a2*, *aldh1a3*, and *rdh10*) were down-regulated in response to

exogenous addition of RA. These genes showed opposite regulation in response to exogenous inhibition of RAL to RA oxidation by DEAB (Fig. 5E). We analyzed the differential expression time series data using another unbiased approach using weighted gene correlation network analysis (WGCNA)(Langfelder and Horvath, 2008). Manual exploration of the results from WGCNA indicated that one of the correlated gene expression modules (most correlated with treatment) contained similar genes as shown in Fig. 5C, supporting the findings from our COMPACT analysis (green module in WGCNA results, Supplemental Table S1; Extended Data 2). Taken together, our results point to a transcriptional feedback control system aimed at maintaining homeostasis of the RA signaling levels to counter the effects of exogenous perturbations, nutritional and environmental, and prevent teratogenic effects.

Clutch-specific heterogeneity of Hox gene expression and feedback control of RA signaling

The analysis above describes RA as a robust signaling pathway capable of responding to environmental disturbances. Our results show that an important aspect of the regulation of robustness involves changes in RA network components (Fig. 5). Interestingly, the PCA analysis suggested clutch-specific heterogeneity in gene expression changes where all samples from the same clutch tended to cluster together (Fig. 3B,C; Supplemental Fig. S3). For these reasons, we analyzed the transcriptional changes in the RA metabolic network within each clutch. We sought to determine whether the clutch-to-clutch variation observed in the RNAseq data is evident even if we utilize a different technical approach to measure the changes in gene expression in a separate set of manipulated embryos. Hence, we generated an independent set of samples to study the dynamic expression changes in RA metabolic network genes using high-throughput real-time PCR (HT-qPCR; Fluidigm Biomark). A separate cohort of six additional clutches (biological repeats labeled G-L) treated with RA or DEAB following the same experimental design (Fig. 3A) used for RNAseq study of the original clutches (A-F). We

designed PCR primers for multiple members of the RA metabolic network and a number of *Hox* genes as targets of the RA signal (Supplemental Table S2). Our results show that heterogeneity between clutches observed in the HT-qPCR data resembles the clutch-to-clutch variation evident in the RNAseq data (Supplemental Figs. S3 and S4).

We ordered the 12 biological repeats (clutches) according to the earliest time at which *hoxa1* returned to the baseline levels (Fig. 6). This ordering intermingled the clutches of the RNAseq and HT-qPCR analysis. Our analysis identified high variability in the response to the RA and DEAB treatments among the individual clutches. Clutches with significant up-regulation of *hoxa1* expression as a result of RA addition showed limited down-regulation in expression in response to inhibition of RA biosynthesis (DEAB treatment; clutches C, L, J, K, H, I in Fig. 6). The opposite response was also observed where DEAB induced a strong response on *hoxa1* expression while the RA treatment induced a mild to very weak response (clutches E, D, F, G, A, B in Fig. 6). Examining the clutch-to-clutch variation in the extent of changes in gene expression revealed a heterogenous correspondence between *hoxa1* and RA metabolic network genes. The suppressors of RA signaling, e.g., *cyp26a1* and *dhrs3*, showed significantly altered expression in clutches (C, L, J, K, H) with larger deviations in *hoxa1* expression and a strong and extended response to the addition of RA. In contrast, the extent of differential expression of the RA producers (e.g., *aldh1a2* and *rdh10*) after RA manipulation was relatively mild and did not fully align with the deviation in *hoxa1* expression (Fig. 6). Such a heterogeneous correlation between extent of feedback regulation and clutch-to-clutch variation in *hoxa1* expression was observed across the RA metabolic network (Supplementary Fig. S5).

Relative robustness ranking in response to perturbation of the RA signal

We sought to analyze the robustness of each clutch in an integrated manner based on the extent of shift in multiple *hox* genes and the complementary feedback regulatory response of the RA metabolic network genes. To this end, we pursued a trajectory-based approach in which the temporal evolution of RA and DEAB treatment groups were compared to the controls based on the regulatory outcome of target gene expression and RA network feedback regulatory gene expression. In this analysis, the samples of all biological repeats (clutches) at all time points were projected onto the first three principal components based on the expression of *hox* genes (*hoxa1*, *hoxa3*, *hoxb1*, *hoxb4*, *hoxd4*) or of RA metabolic network genes. A principal curve was fit to the projected data, representing the trajectory in which the system evolves over time for all clutches combined. Each clutch was visualized separately along the principal trajectory, allowing us to compare the temporal evolution of deviations between treated samples and controls (select clutches shown in Fig. 7A and 7B; all clutches included in Supplemental Fig. S6). We ordered the twelve clutches based on the deviations (distance) between the treated samples and controls along the regulatory outcome trajectories (Fig. 7C). As a multi-gene measure of robustness of each clutch, the net absolute distance between the treated samples (RA or DEAB), and controls was computed along the principal curve in the *hox* gene trajectory map. Our results revealed a wide range of clutch-to-clutch variability in robustness as assessed by the integrated deviation from the control trajectory of multiple *hox* genes (Fig. 7C; Supplemental Fig. S6). Analyzing the clutch-wise variability along the *hox*-based trajectory revealed that the distance between the treatments and controls decreased over time in nearly all the clutches with significant differences in the time taken to close the gap (Fig. 7C). Clutches with low robustness to RA addition showed a significant distance between RA-treated samples and controls along the *hox* gene trajectory at any given time point (e.g., Fig. 7A, clutch C), whereas the most robust clutches showed a decreasing gap between RA-

treated samples and controls over time (e.g., Fig. 7A, clutch E). By contrast, DEAB treatment resulted in an opposite pattern of robustness to that of RA addition (Fig. 7B). For example, clutch C showed the widest deviation from control samples in the *hox* gene trajectory, whereas clutch E showed least deviation (Fig. 7B top row and Fig. 7C). Clutch J exhibited intermediate robustness responses to both the increase and the reduction of RA levels (Fig. 7A,B). The anti-correlated pattern of robustness to increase versus decrease in RA levels suggests a tradeoff in the early embryo in the ability to counter changes in RA levels.

We computed a similar distance-based measure of the feedback regulatory action from the trajectory map based on the RA metabolic network genes (Fig. 7A and 7B bottom rows; Supplemental Fig. S6). The separation of treatment and control along the trajectory based on the regulatory feedback onto RA metabolism was variable across clutches, with a characteristic pattern of reduced deviation over time in several clutches (Fig. 7C, bottom row). There was no significant correlation (or anti-correlation) in the net shift in feedback regulatory action between RA addition versus reduction (Fig. 7F). Importantly, the range of net shift in the RA metabolic network was substantially lower in the case of inhibition of RA biosynthesis as compared to RA addition (compare the span of clusters along the axes in Fig. 7F). This differential range suggests a more constrained ability of the early embryo to mount a feedback regulatory action in response to reduction in RA levels than when countering an increase in RA.

We examined if the differential robustness to direction of change in RA level is related to the extent of feedback regulatory action (Fig. 8). We formulated a "robustness efficiency matrix" (Fig. 8A). The sections of this matrix delineate distinct possibilities based on all permutations of the extent of robustness in the phenotypic outcome, i.e., the net shift in the *hox* gene trajectory, versus extent of the feedback regulatory response, i.e., the net shift in RA metabolic network trajectory. In this scheme, a high robustness (low shift along the *hox* gene

trajectory) may be achieved by a mild or a strong response in the RA metabolic network gene expression, yielding efficient and effective closed-loop feedback control scenarios, respectively (lower quadrants in Fig. 8A). Similarly, the cases of low robustness (high shift along the *hox* gene trajectory) may be characterized by mild or strong gene expression changes in the RA metabolic network components, corresponding to inefficient or ineffective closed-loop feedback control, respectively (upper quadrants in Fig. 8A). In response to an increase in RA levels, half of the clutches were distributed within the efficient and effective zone of the robustness efficiency matrix (Fig. 8B). Five clutches exhibited a substantial shift in *hox* and RA network expression suggesting an inability to correct the RA change, i.e. ineffective response. One clutch was located in an inefficient zone as it exhibited a substantial shift in *hox* gene expression along with a limited extent of gene expression shift in RA metabolic network components. By contrast, the distribution of clutches in response to reduction in RA levels (DEAB treatment) spanned between efficient and inefficient control, characterized by limited gene expression shift in the RA metabolic network while yielding a wide range of robustness in *hox* gene expression (Fig. 8B).

We examined if the clutches with similar levels of robustness and overall feedback regulation use similar strategies for feedback regulation, i.e., whether clutches closely localized within the robustness efficiency matrix show similarity in the genes that are differentially regulated in response to altered RA levels. Interestingly, we found that the identity of differentially regulated genes in the RA metabolic network can vary between clutches co-localized in the robustness efficiency matrix, even if the clutches show directional similarities in overall regulation of production versus reduction of RA levels (Fig. 8C). For example, in response to addition of RA, clutches A, E and F showed similar differential regulation of *dhrs3*, *aldh1a2,* and *cyp26a1*, but diverged in the regulation of other genes such as, *stra6*, *sdr16c5*, *adhfe1*, *rdh13*, *aldh1a3*, and *cyp26c1* (Fig. 8C). Similarly, in response to DEAB treatment,

clutches A, B and D showed downregulation of *dhrs3* and *cyp26a1*, and upregulation of *rbp1*, suggesting feedback aimed at reducing activity of biochemical processes leading to reduction in RA levels, and increasing import of retinol. However, there was much variability across these clutches in the differential expression of *aldh1a2* and *aldh1a3*, i.e., the feedback control aimed at increasing the production of RA. Taken together, the results described in Fig. 7 and 8 provide strong evidence that the early embryo is differentially capable of responding to increase versus decrease in RA levels, with a distinct range of feedback regulatory action mounted between the two scenarios.

DISCUSSION

Robustness of the retinoic acid signaling pathway

Signaling pathway robustness is a central characteristic of all regulatory networks to ensure signaling consistency and reliability. Variations in signaling levels can arise as a result of changing environmental conditions or genetic polymorphisms that can affect the expression or activity level of network components. We describe a systems biology approach to study the robustness of RA metabolism and signaling based on transient manipulation of ligand levels. Gastrula stage *Xenopus laevis* embryos have been reported to contain RA levels, around the 100 nM - 150 nM range (Durston et al., 1989; Kraft et al., 1995; Kraft and Juchau, 1992). In contrast, due to the clear and severe developmental defects induced, *Xenopus* embryos are commonly treated with RA concentrations in the 1 μM to 10 μM range to perturb this signaling pathway (Sive et al., 1990; Taira et al., 1994). To study the robustness of RA signaling in the physiological range, we first performed titration experiments (1 nM - 1 μM). These results showed that by increasing the RA levels by as little as about 10% (10 nM) we could consistently induce expression changes in RA-regulated genes in the presence of this treatment.

Interestingly, embryo treatments with RA concentrations in the physiological range exhibit very slight developmental malformations suggesting the induction of compensatory mechanisms to control morphogen signaling and prevent abnormal gene expression (Hollemann et al., 1998; Reijntjes et al., 2005; Sive et al., 1990). We obtained similar results when we reduced the levels of RA by either blocking the biosynthesis (DEAB treatment) or by targeting this ligand for degradation (CYP26A1 overexpression). Also, multiple loss-of-function studies, described mild developmental malformations induced by RA signaling reduction as in the present study (Blumberg et al., 1997; Hollemann et al., 1998; Janesick et al., 2014; Koide et al., 2001; Kot-Leibovich and Fainsod, 2009; Shabtai et al., 2018; Sharpe and Goldstone, 1997; Shukrun et al., 2019). Therefore, increased or decreased RA levels in the physiological range result in mild developmental defects, suggesting the activation of compensatory mechanisms. We show that one approach to overcome the robustness of RA signaling is to interfere with the metabolic/signaling network at two different steps as in the case of DEAB together with CYP26A1. A possible explanation for this outcome is that manipulating the RA network at more than one point hampers its ability to efficiently respond to changes in RA levels and establish an efficient feedback regulatory response.

RA signaling robustness was further analyzed taking advantage of RNAseq to implement a transcriptome-wide analysis of the changes induced by the RA manipulation and the temporal kinetics of the restoration of normal gene expression patterns. Transcriptome analysis of the control and the RA manipulated embryos by PCA revealed no significant differences between the control and treated (DEAB or RA) samples. The main expression differences observed corresponded to the normal transcriptomic changes resulting from the progression through embryogenesis. The close clustering of the RA-manipulated and control samples at each time point probably reflects the robustness of this signaling pathway. Alternatively, the treatments were inefficient, a possibility we could rule out by qPCR screening of all RNA samples for

Hox expression changes prior to sequencing and subsequent computational analysis of the RNAseq data for individual gene expression shifts. Therefore, the PCA analysis supports the activation of an efficient robustness response of the RA network to maintain normal, non-teratogenic, expression levels during early gastrulation.

Retinoic acid metabolism is altered as part of the robustness response

The PCA analysis clearly supports the robustness of RA signaling when manipulated within the physiological range of concentrations. Then, how is this robustness achieved? What are the changes in the RA network that bring about this robustness? The initial qPCR analysis also provided insights on changes taking place to achieve the RA robustness. In-depth kinetic analysis of RA target genes affected by the treatment revealed abnormal expression levels at the end of the manipulation (t=0), and for some genes, we observed a return to normal expression levels already after 1.5 hours from the end of the treatment. Genes encoding components of the RA metabolic network also exhibited abnormal expression levels at t=0, and interestingly, their return to normal transcript levels was delayed beyond the time required for the RA targets to reach normal expression. This scenario suggests that the RA metabolic network through an RA-dependent feedback regulatory mechanism is altered in an attempt to restore normal signaling and target gene expression levels. Multiple reports have described the regulation of RA network component expression by RA itself. Most of these studies deal with RA treatments resulting in the up-regulation of enzymes involved in the suppression or reduction of RA signaling like CYP26A1, ADHFe1, and DHRS3, and down-regulation of RA producers (anabolic enzymes) like RALDH2 and RDH10 (Chen et al., 2001; Dobbs-McAuliffe et al., 2004; Fujii et al., 1997; Hollemann et al., 1998; Kam et al., 2013; Sandell et al., 2012; Shabtai et al., 2017; Sonneveld et al., 1998; Strate et al., 2009).

In an attempt to understand how extensive is this kinetic response to transient RA manipulation, we pursued a transcriptome-wide analysis of the recovery kinetics. Out of the 27 possible kinetic patterns, only 10 were represented in any of the treatment or control samples, and only five patterns were exhibited by a substantial number of genes (n>100). These observations suggest that among the RA-regulated genes, direct or indirect, there is a limited number of possible regulatory outcomes either in an attempt to normalize RA levels, i.e. robustness, or as target genes. Although this classification is qualitative and there might be differences in intensity, it suggests a limited repertoire of RA regulatory responses. To further understand the regulation of RA targets we performed a comparative analysis of the patterns observed during increased and decreased RA levels using our unbiased approach, COMPACT (Kuttippurathu et al., 2016). This analysis revealed that most genes (75.40%) responding to RA manipulation and recovery exhibited a response to either increased or decreased RA levels. Only 48 genes out of 553 (8.67%) exhibited reciprocal responses to both, increased and decreased RA levels. Interestingly, many of these genes are involved in RA metabolism or signaling, in agreement with their function in maintaining non-teratogenic RA levels.

The qPCR and transcriptomic analysis also provided insights on changes taking place to achieve the RA robustness. Analysis of RA target genes and genes encoding components of the RA metabolic and signaling network suggests that the RA metabolic network through an RA-dependent feedback regulatory mechanism is altered in an attempt to restore normal signaling levels. Multiple reports have described the regulation of individual RA network components by RA itself (Chen et al., 2001; Dobbs-McAuliffe et al., 2004; Fujii et al., 1997; Hollemann et al., 1998; Kam et al., 2013; Sandell et al., 2012; Shabtai et al., 2017; Sonneveld et al., 1998; Strate et al., 2009). Our results provide an integrative network-wide view that incorporates the concerted feedback regulation of multiple pathway components to achieve normal signaling under changing environmental conditions. The temporal discrepancy in the

return to normalcy between targets and network components and the network-wide changes in expression patterns suggests a response taking place at multiple levels. The initial response to changes in RA levels will most probably be mediated by the actual enzymes and factors already present in the cell. In parallel, the same change in RA signaling will initiate a transcriptional response which in the case of increased RA will involve not only the up-regulation and eventual enhancement of the enzymatic RA suppressor activity, i.e. DHRS3, ADHFe1, and CYP26A1, but importantly, a complementary down-regulation and activity reduction in RA producing enzymes (RALDH2 and RDH10). This transcriptional response will necessarily exhibit a slight delay until fully functional as the network component genes will have to undergo transcription, followed by translation and post-translational modifications, when required.

We observed that the expression of RA network components exhibits some oscillatory behavior close to control expression levels, probably as a result of the fine-tuning of the RA signal. This fine-tuning of the RA signal levels coupled to the inherent delay in the transcriptional response could transiently result in the inversion of the overall signaling direction, and an oscillatory transcriptional behavior. In a few instances such paradoxical observations of RA signaling outcome following RA manipulation, i.e. overcompensation, have been reported (D'Aniello et al., 2013; Lee et al., 2012; Rydeen et al., 2015). These observations identify a very dynamic feedback regulatory network continuously fine-tuning itself in response to perturbations.

Genetic variability affects the RA robustness

Although the PCA analysis showed high robustness as evidenced from the clustering of the RA manipulated samples together with the controls from the same clutch, there was variability evident between clutches. The transcriptomic analysis summarized the results of six

biological repeats, each one from a different clutch of embryos, each one originating from eggs laid by a single female. In our experiments, we utilized commercially available *Xenopus laevis* laboratory stocks which are outbred and exhibit extensive genetic variability (Savova et al., 2017). Therefore, we propose that one of the main differences between clutches in their response to RA manipulation is probably the result of genetic variability. Formally, technical issues could somehow account for some of the clutch-to-clutch variability uncovered in the PCA analysis. To further support the genetic basis of the RA response, we prepared samples from six additional biological repeats that were analyzed by a different method. This cohort of six additional clutches was analyzed by high-throughput real-time PCR (HT-qPCR; Fluidigm Biomark) focusing on the *Hox* genes as RA targets in addition to components of the RA network following transient RA manipulation. This focused qPCR analysis showed that the new clutches exhibit overlapping responses to RA manipulation to the clutches analyzed by RNAseq. These observations further support our initial suggestion of involvement of genetic variability. A combined distance-based analysis along the trajectories of the RA manipulated samples from the respective controls showed that the new clutches (G-L) intermingled with the original biological repeats (A-F) along the whole spectrum of observed responses.

The 12 biological repeats analyzed for the kinetics of RA robustness uncovered a variability in the efficiency of the response to transient manipulation of this pathway. We propose that this variability is probably greatly affected by genetic polymorphisms that can result in amino acid changes in enzyme sequences (missense mutations), affecting their activity or single nucleotide changes affecting the transcriptional regulation of the gene and its response to RA changes (Evans and Kwon, 2015; Michiue et al., 2017; Savova et al., 2017; Suzuki et al., 2017). Studies in humans have shown the involvement of genetic variability in absorption and metabolism components in determining the status and bioavailability of vitamin A for RA biosynthesis (Borel and Desmarchelier, 2017). We have recently shown that gene expression

levels can vary extensively between *Xenopus laevis* clutches (Leibovich et al., 2020). Also, a recent comparative study of the genetic variability between two *Xenopus laevis* strains revealed extensive genetic polymorphisms (Savova et al., 2017). We mined the Savova et al. (2017) data identifying multiple polymorphisms in RA network components (Supplemental Table S3). All these observations support the potential contribution of genetic variability in the differential robustness, intensity and response composition, observed between embryo clutches.

Our analysis of the transcriptional response to RA manipulation revealed differing patterns between clutches in the specific RA network component changing and whether the change involves up- or down-regulation. These observations suggest that different genetic backgrounds ultimately respond differently to the same RA pathway disturbance. The RA network includes multiple components, i.e. enzymes, whose biochemical activity overlaps or is very similar. The RA producing genes, *aldh1a1, aldh1a2,* and *aldh1a3*, also known as *raldh1, raldh2,* and *raldh3* respectively are one example. All three enzymes oxidize retinaldehyde to produce RA (Cunningham and Duester, 2015; Kedishvili, 2016, 2013; Shabtai et al., 2016). Some of the differences between them apparently include enzymatic efficiencies and their expression patterns including location, timing, and intensity (Blentic et al., 2003; Chen et al., 2001; Lupo et al., 2005; Romand et al., 2004; Shabtai et al., 2018). A similar situation can be argued for enzymes with RA degrading or biosynthetic suppressing activity like CYP26A1, B1, and C1, or DHRS3, ADHFe1, RDH13 and others (Belyaeva et al., 2017, 2008; Hollemann et al., 1998; Shabtai et al., 2017; Sonneveld et al., 1998). Some of these enzymes can reduce or prevent the production of retinaldehyde while others make the RA biologically inactive targeting it for degradation. Irrespective of the biochemical mechanism, these enzymes function to prevent excessive RA signaling. Therefore, any polymorphisms affecting their enzymatic efficiency or their expression level could have major effects on RA signaling with potentially severe teratogenic outcomes. Our clutch-specific analysis revealed

that apparently different genetic backgrounds try to adapt by manipulating different network components in an attempt to reach the same outcome, i.e. the homeostasis of RA signaling.

In a number of instances, the response to environmental changes has been shown to also depend on the genetic composition of the organism. Fetal Alcohol Spectrum Disorder (FASD) has been shown to be induced as a result of fetal exposure to alcohol during pregnancy (Jones et al., 1973; Koren, 2012; Lemoine et al., 1968)). Recent studies have shown a close etiological link between FASD and a reduction in RA biosynthesis through competitive inhibition between ethanol clearance and RA biosynthesis (Shabtai et al., 2018). Genetic polymorphisms can affect the malformation severity following alcohol exposure in experimental models (Boehm et al., 1997; Loucks and Carvan, 2004; Shukrun et al., 2019). Similarly, genetic polymorphisms in the human population can affect the outcome of alcohol exposure identifying protective and high-risk alleles of enzymes involved in maternal alcohol clearance (Eberhart and Parnell, 2016; Green and Stoler, 2007). In contrast, the early embryo does not express the full complement of alcohol metabolizing enzymes. Due to the overlap with RA biosynthesis (Duester, 1991; Pullarkat, 1991), some of the RA metabolic enzymes are diverted to alcohol clearance at the expense of RA production (Shabtai et al., 2018; Shabtai and Fainsod, 2018). Also, these enzymatic activities are affected by genetic polymorphisms impacting on the robustness of the RA response and the severity of the FASD induced.

Retinoic acid signaling changes due to environmental changes and disease risk

RA levels are tightly regulated throughout life at multiple levels to prevent aberrant signaling and as a consequence, abnormal gene expression as a result of diet and other environmental insults ((Blaner, 2019; Blaner et al., 2016); (Ghyselinck and Duester, 2019; Kedishvili, 2016); (Coberly et al., 1996; Lie et al., 2019; Paganelli et al., 2010; Shabtai et al.,

2018)). During early embryogenesis, when RA biosynthesis initiates and it is restricted to a limited repertoire of metabolic enzymes, this regulation is particularly important and susceptible to changes. Our results complement and expand previous studies showing that quantitative, spatial and temporal regulation of the RA signal relies in part on regulation of the expression and the activity of biosynthetic and metabolizing enzymes as a network (Dobbs-McAuliffe et al., 2004; Ghyselinck and Duester, 2019; Kedishvili, 2016; Zhong et al., 2018).

For several decades, retinoic acid signaling has been the focus of intensive study due to the severe teratogenic effects of abnormal levels and its involvement in the regulation of numerous embryonic processes, oncogenes, and other signaling pathways. While the exposure of embryos or cells to RA induces dramatic developmental changes and malformations, treatment of the same embryos with retinol, the RA precursor, requires much higher concentrations (~100X) to induce similar defects (Durston et al., 1989). Several models could explain the different teratogenic potential of the precursor (retinol) or its final product (RA). In both instances, members of the CYP26 family of cytochrome P450 enzymes should partially neutralize the RA added or produced (Dobbs-McAuliffe et al., 2004; Duester et al., 2003; Hollemann et al., 1998; Sakai et al., 2001). The main difference then becomes the fact that retinol has to go through RA biosynthesis while RA is already the final active signaling ligand (Duester, 2008; Kedishvili, 2016; Parés et al., 2008). Retinol has to go through two sequential oxidation reactions to produce RA in an equimolar ratio. The first oxidation reaction is reversible which in turn reduces the substrate availability for the second oxidation reaction. Importantly, many of these reactions are performed by enzymes whose expression is regulated by RA itself. On the other hand, treatment with RA only allows for its inactivation by CYP26 enzymes as the only regulatory resource. Therefore, the reduced teratogenic efficacy of the retinol treatment could be the result of reduced conversion to RA as part of the feedback

regulation of this network, i.e. robustness, while RA treatment is very restricted in its robustness response.

We obtained evidence of the RA signaling robustness employing several experimental approaches. In all instances, we observed a fast response to the RA manipulation such that at the transcriptome level, the treated samples were not significantly different from controls. All our experiments were performed by either partially inhibiting the endogenous levels of RA, or by slightly increasing (about 10% increase) the physiological content of RA in the embryo. Under these conditions, the RA robustness of the embryo efficiently regulates and normalizes the transcriptome as a whole via feedback. Based on the comparative analysis of the 12 clutches (genetic backgrounds), we can suggest that robustness efficiency will have a threshold beyond which it will become ineffective in restoring normal RA signaling. Our clutch analysis suggests that this threshold might be strongly dependent on genetic polymorphisms affecting enzymatic activity or gene expression parameters. In support, a threshold or toxicological tipping point for RA signaling was recently described in a cell-based model (Saili et al., 2019). The clutch analysis also showed that the network response, i.e. the genes actually up- or down-regulated, is also dependent on genetic variability like promoter polymorphisms. Then, the developmental malformations arising from environmental insults on RA signaling largely depend on genetic polymorphisms which will determine the efficiency and threshold of the response and the actual network components comprising such a response.

MATERIALS AND METHODS

Embryo culture

Xenopus laevis frogs were purchased from Xenopus I or NASCO (Dexter, MI or Fort Atkinson, WI). Experiments were performed after approval and under the supervision of the

Institutional Animal Care and Use Committee (IACUC) of the Hebrew University (Ethics approval no. MD-17-15281-3). Embryos were obtained by *in vitro* fertilization, incubated in 0.1% MBSH and staged according to Nieuwkoop and Faber (Nieuwkoop and Faber, 1967).

Embryo Treatments

all-trans Retinoic acid (RA), Dimethyl sulfoxide (DMSO), and 4-Diethylaminobenzaldehyde (DEAB), were purchased from Sigma-Aldrich (St. Louis, Missouri). Stock solutions of RA, and DEAB, were prepared in DMSO. Two-hour treatments of 10 nM RA, or 50 μM DEAB, were initiated during late blastula (st. 9.5) and terminated at early gastrula (st. 10.25) by three changes of 0.1% MBSH and further incubation in fresh 0.1% MBSH for the desired time.

Total RNA purification from embryos and cDNA preparation

For each sample, 5-10 staged embryos were collected and stored at -80°C. RNA purification was performed using the Bio-Rad Aurum Total RNA Mini Kit (according to the manufacturer's instructions). RNA samples were used for cDNA synthesis using the Bio-Rad iScriptTM Reverse Transcription Supermix for RT-qPCR kit (according to the manufacturer's instructions).

Expression analysis

Quantitative real-time RT-PCR (qPCR) was performed using the Bio-Rad CFX384 thermal cycler and the iTaq Universal SYBR Green Supermix (Bio-Rad). All samples were processed in triplicate and analyzed as described previously(Livak and Schmittgen, 2001). All experiments were repeated with six different embryo batches. qPCR primers used are listed in (Supplemental Table S2).

RNASeq data analysis

Sequencing was performed at the Thomas Jefferson University Genomics Core using Illumina HiSeq 4000. Reads were mapped to the genome using the Xenopus laevis 9.1 genome with STAR alignment and a modified BLAST and FASTQC in the NGS pipeline (STAR average mapped length: 142.34). Annotation of the mapped sequencues using *verse* identified 31535 genes. Raw counts were further filtered for non-zero variance across all samples resulting in 31440 scaffold IDs.

High throughput qPCR

cDNA samples were directly processed for reverse transcriptase reaction using SuperScript VILO Master Mix (Thermo Fisher Scientific, Waltham, MA), followed by real-time PCR for targeted amplification and detection using the Evagreen intercalated dye-based approach to detect the PCR-amplified product.

Intron-spanning PCR primers were designed for every assay using Primer3 and BLAST for 24 genes from Retinoic Acid metabolism and target pathway (Supplemental Table S2). The standard BioMark protocol was used to preamplify cDNA samples for 22 cycles using TaqMan PreAmp Master Mix as per the manufacturer's protocol (Applied Biosystems, Foster City, CA, USA). qPCR reactions were performed using 96.96 BioMark Dynamic Arrays (Fluidigm, South San Francisco, CA, USA) enabling quantitative measurement of multiple mRNAs and samples under identical reaction conditions. Each run consisted of 30 amplification cycles (15 s at 95°C, 5 s at 70°C, 60 s at 60°C). Ct values were calculated by the Real-Time PCR Analysis Software (Fluidigm). Samples were run in triplicate for the 24 genes. The primers in the first pre-amplification group selectively bind for the long isoforms of the genes. In the second pre-amplification group, primers were selected for the short isoforms only. Third pre-amplification group binds to all the 24 genes. In order to remove the technical variability caused due to long

and short isoform of the genes, Ct value for each gene in a sample was selected as the median value of the three pre-amplification runs. Relative gene expression was determined by the ΔΔCt method. Gapdh was used as a housekeeping gene for normalization of the data.

Data normalization and annotation

Data analysis on raw genes count was performed using the R statistical analysis tool version 3.6.0 on a 64-bit Windows platform. For the RNA-seq data, the raw genes counts were first converted into log2-transformed values using the "regularized log (rlog)" transformation from the DESeq2 package, which minimizes differences between samples for rows with small counts (Love et al., 2014). The gene expression data was then normalized across samples against the experimental variation and batch effects using COMBAT method in R using a non-parametric adjustment (Johnson et al., 2007). Following batch correction, the gene list was filtered for a minimum expression threshold to remove genes with normalized count less than 5 across all 72 samples. The expression data for the remaining genes was normalized using quantile normalization**.** RNA-Seq transcript/array probes IDs were transformed to Official Gene Symbol using merged list from 3 sources: the Xenopus laevis scaffold-gene mapping, DAVID Bioinformatics Resource 6.8 (Huang et al., 2009) or AnnotationData package "org.Xl.eg.db" maintained by Bioconductor (Carlson, 2017). The original scaffold IDs were retained along with the Official Gene Symbols for cross-reference purposes.

Differential gene expression analysis

The normalized data was analyzed using an Empirical Bayes Statistical (eBayes) model that considered the following two variables and their interactions: (1) Treatment (Control, RA, DEAB) and (2) Time post treatment-washout (t = 0, 1.5, 3, 4.5h). Differentially expressed genes were identified based on statistically significant effects of Time, Treatment or an interaction between these two factors. P-values were adjusted for multiple testing using

topTable from *limma* (Ritchie et al., 2015) package in R ($q \leq 0.05$). The significance-filtered differential gene expression data was used in an established Principal Component Analysis (PCA) approach using the *prcomp* function implemented in R. The samples were annotated based on a combination of treatment and time, yielding 12 distinct sample groups. For each of the selected PC, expression of 100 top positively-loaded and 100 top negatively-loaded genes was visualized using a heat map.

Dynamic pattern analysis and COMPACT analysis

First, for each time point for each of the treatment conditions, the gene expression data for all six clutches (A,B,C,D,E,F) was averaged. Within treatment groups RA, DEAB, Control, the gene expression data at time points t=1.5, 3, 4.5h was normalized by subtracting the corresponding 't=0h' group. This average differential gene expression data was then discretized to three levels (+1, 0, −1) based on a fold-change threshold [±2 (up, no or down-regulation)]. Within the three treatment groups, this discretization yielded a dynamic response pattern vector for each gene, encoded by one of 27 (3 levels^3 time-points) possible ordered sets. Counts of genes in each treatment group that follow each of the 27 * 27 (=729) possibilities were compared. Functional enrichment analysis was performed for geneset in various dynamic pattern vectors in the Control conditions, using functions *enrichGO* and *simplify* from the R package "clusterProfiler" (Yu et al., 2012).

COMPACT analysis of RA and DEAB after normalizing to Control

First, for each time point for each of the treatment conditions, the gene expression data for all six clutches (A,B,C,D,E,F) was averaged. Within treatment groups RA and DEAB, the gene expression data were normalized to Control at each time point by subtracting the expression of the Control group at the corresponding time point. This Control-normalized differential gene expression data for both treatment groups was then discretized to three levels (+1, 0, −1) based

on a fold-change threshold [±log2(1.3) (up, no or down- regulation)]. This discretization yielded a dynamic response pattern vector for each gene, encoded by one of 81 (3 levels^4 time-points) possible ordered sets. Subsequently, RA and DEAB groups were compared to count the number of genes corresponding to each of the 81 * 81 (=6561) possibilities; to create a 81×81 matrix representing the comparative dynamic response pattern counts (COMPACT)(Kuttippurathu et al., 2016). For a given COMPACT matrix of comparative conditions RA(vs. Control) and DEAB (vs. Control), the element at the ith row and jth column of the matrix contains the number of genes that show an 'i'th pattern in DEAB and 'j'th pattern in RA. For a coarse-grained version of the detailed 81x81 COMPACT, pattern-vector counts for each treatment group were further aggregated based on the first time-point, yielding 9 groups of pattern vectors per treatment group. The pair of treatment group (RA and DEAB) was then compared to count the number of genes corresponding to each of the 9 * 9 (=81) possibilities.

RA network map and visualization

A schematic representation for the position and functioning of the genes involved in the RA biosynthesis, metabolism, translocation and transcription was formulated from the literature. For each time point for each treatment, expression value for each gene was mapped to the corresponding label in the schematics using a color scale.

Gene correlation and clustering analysis - Gene expression data was analysed for both with and without Control-normalization using Weighted Gene Coexpression Network Analysis (WGCNA) (Langfelder and Horvath, 2008) to identify modules of genes with highly correlated differential expression. We used a soft threshold value of 9 (8 for Control normalized data) to identify the initial gene coexpression modules, followed by a dissimilarity threshold of 0.25 to merge the initial modules into the final set of gene coexpression modules. Identified modules were further correlated with the traits (batch, time, treatment).

Robustness score calculation and principal curve-based trajectory analysis

RNA-seq expression data of (clutches: A,B,C,D,E,F) and additional normalized qPCR expression data (clutches: G,H,I,J,K,L) were independently genewise Z-score transformed. Transformed data was then combined to result into 144 samples (12 clutches * 3 treatments * 4 timepoints). We further selected two subsets of genes: 1) "RA metabolism genes" [aldh1a2.L, aldh1a3.L, crabp2.L, crabp2.S, cyp26a1.L, cyp26a1.S, cyp26c1.L, cyp26c1.S, dhrs3.L, rbp1.L, rdh10.L, rdh10.S, rdh13.L, rdh14.L, sdr16c5.L, stra6.L]. This set represents the feedback regulatory mechanism utilised in response to the RA levels perturbations. 2) "HOX genes" [hoxa1.L, hoxa1.S, hoxa3.S, hoxb1.S, hoxb4.S, hoxd4.L] representing the phenotypic outcome from the treatment. For each gene set, the PCA scores for the combined data was first calculated using R function *prcomp* and then the scores from the first three principal components (PC1, PC2 and PC3) are used to learn a 3-dimensional principal curve using the function *principal_curve* from R package princurve. Two sets of points are specified for the 'start' parameter for this function, which determines the origin and direction of the curve: (1) The centroid of the 0h-Control samples from all twelve clutches, and (2) centroid of all the remaining 132 samples. For each geneset (RA metabolism genes and HOX genes), for each clutch (A-L), for each treatment (RA or DEAB), a "net absolute expression shift" can be calculated as the sum of distances along the principal curve, of the treatment samples from the corresponding control samples:

$$s.hox_{cl}^{RA} = \sum_{t} abs\left(\frac{\lambda.hox_{cl}^{RA(t)} - \lambda.hox_{cl}^{Control(t)}}{max(\lambda.hox)}\right)$$

where, $\lambda.hox_{cl}^{RA(t)}$ is the arc-distance from the beginning of the curve, for the "*RA treatment samples*" at time point "*t*", for clutch "*cl*" for the principal curve learned for the geneset "*Hox genes*" (Returned as the parameter "*lambda*" from the principal curve function). The expression shift calculation allows ranking and sorting clutches along measures 'HOX shift' ($s.hox_{cl}^{treatment}$) and 'RA Network shift' ($s.metabolism_{cl}^{treatment}$). A higher HOX shift for

a clutch for a treatment indicates that the clutch is more robust to that particular treatment/perturbation. Furthermore, clutches were mapped onto the conceptual map across the spectrum of "HOX shift" and "RA Network shift" divided into hypothetical quadrants of Effective or Ineffective regulation, or Efficient or Inefficient regulation.

Availability of supporting data/additional files

The raw and normalized datasets for the RNAseq and HT-qPCR data are available online as Gene Expression Omnibus datasets via SuperSeries GSE154408 containing RNAseq data: GSE154399 and HT-qPCR data: GSE154407.

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ABBREVIATIONS USED

COMPACT: Comparative Matrix of Pattern Counts

DEAB: 4-diethylaminobenzaldehyde

PCA: Principal Component Analysis

PCR: Polymerase Chain Reaction

RA: retinoic acid

WGCNA: Weighted Gene Coexpression Network Analysis

AUTHOR CONTRIBUTIONS

R.V. and A.F. conceived and supervised the study and designed the experiments and analysis methodology. L.B-K., M.G., K.K., and A.F. performed embryo experiments and real-time PCR assessment and developed the figures. A.B. performed the initial analysis of the RNAseq data. S.A. conducted the high-throughput PCR validation of RNAseq results. M.P. conducted the analysis of transcriptomics and HT-qPCR data and performed the network and trajectory analyses and developed the figures. M.P., R.V., and A.F. interpreted the results and drafted the manuscript.

ETHICS DECLARATIONS

The authors declare no competing interests.

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FIGURE LEGENDS:

Figure 1. Phenotypic robustness of the retinoic acid metabolic pathway. Retinoic acid levels were manipulated in *Xenopus laevis* embryos. Inhibition of RALDH activity with DEAB or CYP26A1 overexpression to render retinoic acid inactive were utilized to reduce levels of this signal. **(A)** Schematic diagram of the retinoic acid metabolic pathway and the steps affected. **(B)** Control embryo at st. 27. **(C)** Embryo injected with capped RNA (0.8 ng) encoding the CYP26A1 enzyme. A lineage tracer (ß-galactosidase RNA) was included to ensure a dorsal injection. **(D)** Embryo treated with DEAB (50 µM) from the midblastula transition until st. 27. **(E)** Embryo treated with DEAB and injected with *cyp26a1* mRNA.

Figure 2. Kinetics of the recovery from RA manipulation. Embryos were transiently treated with either 10 nM RA (A,B), or 50 µM DEAB (C,D). Treatments were initiated during late blastula (st. 9.5), and by early gastrula (st. 10.25) the treatments were washed. RNA samples were collected at different time points during the recovery period. The response of RA target genes and genes encoding RA metabolic enzymes was studied by qPCR. Statistical significance (Student's t-test) was calculated compared to the expression level at the end of the treatment (t_0). *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$; ****, $p<0.0001$; ns, not significant.

Figure 3. Retinoic acid signaling recovery in a kinetic analysis. (A) Schematic description of the experimental design to study the robustness of RA signaling and the transcriptomic changes involved in the maintenance of signaling robustness. **(B)** Principal Component Analysis of all six biological replicates revealed sample separation based on developmental stages. The samples grouped largely based on developmental time points following treatment, with the RA or DEAB groups clustering with the control samples. The t=0, 1.5, 3 and 4.5h samples group were all distinctly separated by Principal Component 1. Principal Component 2 separated samples at intermediate time points (t=1.5 and 3h). The samples do not appear to separate based on experimental manipulation of RA levels for either PC1 or PC2. **(C)** Principal Component 10 revealed limited sample separation based on RA manipulation. **(D)** Heatmap of gene expression of the top-100 positive and top-100 negative loadings corresponding to PC1, PC2 and PC10. A subset of the genes are highlighted based on their relevance to early developmental processes.

Figure 4. Comparison of the differential gene expression patterns across the two treatment groups compared to controls. (A) Genes were grouped into 27 discretized expression patterns based on three possible outcomes of expression (yellow: up-regulation, blue: down-regulation, grey: no change) at each of the three recovery time points compared to the t_0 sample. For example, the pattern marked blue at only the last time point (first row) represents late down-regulation above a 2-fold change threshold. The counts next to the patterns indicate the number of genes that show the corresponding expression pattern in each of the two treatment groups and the controls. The pattern counts are based on a differential regulation threshold of 2-fold change compared to t=0. Only ten out of 27 dynamic patterns were exhibited by at least one gene and are included in the figure. The majority of genes showed differential regulation at 3 and 4.5h. Of note, no genes showed a biphasic response of up- and down-regulation within 4.5h. The progressive up-/down-regulation of genes constitute a dominant feature of the early developmental process, which in many instances represents a restoration of normal expression levels. **(B)** The Gene Ontology biological processes statistically enriched in the control group are indicated alongside the pattern counts. **(C)** Venn diagrams to compare the overlap between the two treatments and control, illustrated for three differential gene expression patterns. The number of genes that show a similar differential expression pattern across two treatments and control is indicated in the middle of the Venn diagrams. The number of genes that showed similar differential expression patterns only in one or two experimental groups are also indicated in the corresponding overlapping regions of the Venn diagrams. Black, control; Orange, DEAB; Blue, RA.

Figure 5. Comparative pattern analysis to uncover the genes showing distinct changes in expression dynamics in response to opposing perturbations of the RA signal. (A) Differential expression patterns with at least one gene in RA (or DEAB) versus control groups. **(B)** COMPACT matrix comparing gene expression changes due to RA and DEAB relative to control. Of the potential 81x81 patterns, only the subset of 32 x 32 patterns with non-zero number of genes in either perturbation group are shown. The gene counts were grouped within related patterns based on the time of initial up- or down-regulation. Extended Data 1 contains a version of the COMPACT matrix shown with the gene identifiers corresponding to the counts. **(C)** Dynamic expression patterns of genes showing opposite changes in response to RA and DEAB treatments. This set of genes contains several components of the RA metabolism and gene regulatory network. **(D)** RA metabolic network showing synthesis and degradation

of RA as well as a few known transcriptional regulatory targets. **(E)** Mapping the differential expression data onto the RA network shown in panel D to highlight the differences in regulation of biosynthesis versus degradation of RA signal between RA and DEAB groups.

Figure 6. Clutch-wise differential expression dynamics of select RA network genes and targets. The clutches are ordered left to right based on the earliest time at which *hoxa1* expression returned to the baseline levels. The data was combined from RNAseq (clutches A-F) and HT-qPCR (clutches G-L).

Figure 7. Trajectory analysis to compare the extent of multi-gene shift away from and return to control levels and rank clutch-wise robustness. (A) 3-dimensional principal curves for two separate gene sets: "RA pathway genes" and "HOX genes", showing projections of the sample points on the curve. Black star indicates the beginning of the curve for the distance measurement along the path. **(B)** Principal curves with the projection of Control and treatment samples only for the clutch ranked "most shifted" or "least shifted". Ranking of clutches is based on the net (absolute) normalized shift of treatment samples from the corresponding Control sample for each time point. **(C,D)** A normalized expression shift profile calculated from the principal curve as the arc distance between the treatment and the corresponding control. Clutches are rank-ordered from lowest to highest net expression shift for HOX genes in the RA group. **(E,F)** Net (absolute) normalized shift of Hox genes (panel E) or RA metabolism genes (panel F) for each clutch over all time points, calculated for both RA and DEAB treatment. Clutches A-F data from RNA-seq , clutches G-L data from HT-qPCR.

Figure 8. Differential robustness to direction of change in RA level is related to the effectiveness of feedback regulatory action. (A) A schematic diagram of robustness efficiency matrix delineating the scenarios arising from all combinations of robustness and feedback response. **(B)** Distribution of clutches across the zones of the robustness efficiency matrix for RA and DEAB groups relative to the control. The letters indicate the distinct clutches. **(C,D)** Mapping the differential expression data onto the RA network shown in Fig. 5D to highlight the heterogeneity of differential regulation of RA network components amongst clutches closely situated in the robustness efficiency matrix (panel B). Clutches A,E, and F

showed similar robustness efficiency in response to RA treatment (panel C), whereas clutches A, B, and D showed similar robustness efficiency in response to DEAB (panel D).

SUPPLEMENTAL INFORMATION:

Supplemental Figure S1. Retinoic acid manipulation in the physiological range. Embryos were treated with increasing concentrations of all-*trans* RA from 1 nM to 1 μM. Treatments were initiated at the midblastula transition (st. 8.5) and RNA samples were collected at early (st. 10.25) and late (st. 12) gastrula. The response of the RA metabolic and target genes was studied by qPCR. (A) *hoxb1*. (B) *cyp26a1*. (C) *dhrs3*. (D) *raldh2* (*aldh1a2*). (E) *raldh3* (*aldh1a3*). (F) *rdh10*. Statistical significance (Student's t-test) was calculated compared to the expression level in the control group. *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$; ns, not significant.

Supplemental Figure S2. Genes affected by RA manipulation. Heatmap of gene expression of the top-100 positive and top-100 negative loadings corresponding to PC1, PC2 and PC10.

Supplemental Figure S3. Differential robustness to RA manipulation between embryo clutches. Principal Component Analysis of RNAseq data revealed heterogeneity across developmental stages and treatments. (A) Distribution of samples along PC1 and PC2 axes. (B) Distribution of samples along PC1 and PC10 axes. The letters represent the six distinct biological repeats, clutches A-F.

Supplemental Figure S4. HT-qPCR analysis of RA network components. Principal Component Analysis of HT-qPCR data revealed heterogeneity across developmental stages and treatments. (A) Distribution of samples along PC1 and PC2 axes. (B) Distribution of samples along PC1 and PC10 axes. (C) Heatmap of time series differential expression of RA network genes.

Supplementary Figure 5. Clutch-wise heterogeneity in the response of RA network genes following RA manipulation. Clutch-wise differential expression dynamics of RA network genes. The clutches are ordered left to right according to the time taken for recovery of hoxa1.L.

Supplemental Figure S6. Trajectory analysis to compare the extent of multi-gene shift away from and return to control levels and rank clutch-wise robustness. Clutches are ordered left to right according to the extent of net deviation between control and RA treatment along the HOX gene trajectory. High deviation corresponds to low robustness and vice versa. (A) RA and control groups are highlighted along the trajectories. (B) DEAB and control groups are shown.

Supplemental Table S1. Weighted Gene Correlation Network Analysis (WGCNA) of the time series RNAseq data. The green module is shown here.

Supplemental Table S2. List of HT-qPCR primers corresponding to the Hox genes and RA metabolic network.

Supplemental Table S3. RA network component polymorphisms between *Xenopus* strains. Based on Savova et al. (2017).

Extended Data 1. The Excel file contains the complete list of gene identifiers represented in the COMPACT matrix corresponding to Figure 5B.

Extended Data 2: The source Excel file contains all the gene expression modules from WGCNA.

Supplemental Table S1. Weighted Gene Correlation Network Analysis (WGCNA) of the time series RNAseq data. The green module is shown here. The attached Extended Data 2 source Excel file contains all the gene expression modules from WGCNA.

Gene ID	Gene Names	Module Numbers	Module Colors	RA vs. Control pattern	DEAB vs. Control pattern
Xelaev18001038	LOC108703560	5	green	1_1_1_1	0_0_-1_-1
Xelaev18002824	sema3f.L	5	green	0_0_1_1	0_0_0_-1
Xelaev18006802	nfib.L	5	green	0_0_1_1	0_0_0_-1
Xelaev18007035	cmtm5.L	5	green	1_1_1_0	0_0_-1_-1
Xelaev18010181	tdgf1.2.S	5	green	0_1_1_0	0_0_0_-1
Xelaev18012533	LOC108708243	5	green	0_0_0_1	0_0_0_-1
Xelaev18013332	prph.L	5	green	1_1_1_1	0_0_0_-1
Xelaev18014991	hnf1b.S	5	green	0_1_1_0	0_0_-1_-1
Xelaev18015206	LOC108709115	5	green	0_0_1_0	0_0_0_-1
Xelaev18024402	pax6.S	5	green	0_0_1_0	0_0_0_-1
Xelaev18024482	LOC108715248	5	green	0_1_1_0	0_0_0_-1
Xelaev18025805	abhd14a.S	5	green	0_1_0_0	0_0_-1_0
Xelaev18030578	LOC108718689	5	green	0_1_1_0	0_0_-1_-1
Xelaev18030982	hoxa1.L	5	green	1_1_1_0	-1_-1_-1_-1
Xelaev18031638	gcnt2.L	5	green	0_0_0_1	0_0_-1_0
Xelaev18033067	hoxa1.S	5	green	1_1_1_0	-1_-1_-1_-1
Xelaev18033068	hoxa2.S	5	green	1_1_0_0	0_-1_-1_-1
Xelaev18033069	hoxa3.S	5	green	1_0_0_0	0_0_0_-1
Xelaev18033072	hoxa5.S	5	green	0_0_1_0	0_0_0_-1
Xelaev18034595	cyp26c1.L	5	green	0_1_1_1	0_-1_-1_-1
Xelaev18035730	dhrs3.L	5	green	1_1_1_0	-1_0_0_-1
Xelaev18036884	cyp26a1.S	5	green	1_1_1_0	-1_-1_0_0
Xelaev18036885	cyp26c1.S	5	green	1_1_1_1	0_0_-1_-1
Xelaev18037155	neurog3.S	5	green	0_1_0_0	0_0_0_-1
Xelaev18037556	LOC108697667	5	green	1_1_1_0	0_-1_0_0
Xelaev18038437		5	green	0_0_1_0	0_0_0_-1
Xelaev18039368_meis3.L	meis3.L	5	green	0_1_0_0	-1_-1_0_0
Xelaev18041724	LOC108699981	5	green	0_1_1_0	0_0_-1_-1
Xelaev18044027	LOC108701808	5	green	0_1_1_0	0_-1_0_0
Xelaev18044028		5	green	1_1_1_0	0_0_0_-1
Xelaev18044734	hoxd1.L	5	green	0_1_0_0	-1_0_0_0
Xelaev18045501	LOC100489456.L	5	green	0_0_1_0	0_0_-1_-1
Xelaev18045983	hoxb1.S	5	green	0_1_0_0	0_-1_-1_-1
Xelaev18047280	gbx2.1.L	5	green	0_1_1_1	0_-1_-1_-1

Supplemental Table S2. List of PCR primers corresponding to the *hox* genes and RA metabolic network for RT-qPCR and HT-qPCR analysis.

Gene	*Forward primer*	*Reverse primer*
RT-qPCR		
dhrs3.L	CAGGCGCAAGAAATCCTAAG	CAAAGGCCACGTTACAGGAT
aldh1a2.L	ATGTTTGCCTGGAAGA	GAGAGCAGTGAGCGGA
cyp26a1.S	CGATTCCTCAAGGTTTGGCTTCA	ATTTAGCGGGTAGGTTGTCCACA
hoxb1.L	TTGCCCCAGTGCCAATGAC	TCCCCCTCCAACAACAAACC
hoxd1.S	TTCTTGCGGGGATGTTTTAG	CCGACTGGCATAAAGGAATG
hoxb4.S	CCAAGGATCTGTGCGTCAA	GCAGGATGGAGGCGAACT
gapdh	GCTCCTCTCGCAAAGGTCAT	GGGCCATCCACTGTCTTCTG
HT-qPCR		
aldh1a2.L	ATGTTTGCCTGGAAGATTGC	GAGAGCAGTGAGCGGAGTCT
cyp26c1.L	AAACGGGTTCCTTTCTGTGT	GCTTCGATTTACCCTACACTCTT
hoxb1.S	CCAACTTCACGACCAAACAA	GTGGCTGCGATCTCTACTCTC
hoxd4.L	TTCCCTACCATCATTCCTTTC	GAGTCATTATTTCCTGCTTTCTTT
rbp1.L	TGGAAATGCGAGTAGGAGATG	GGGATGGTGGTTTATTGTGTG
rdh13.L	CAAGTGTCTACCTGGCTGTTG	CCCAGAGTTTCCTTGCAGTT
rdh14.L	TGCCCGTACACAAAGACAGA	GAGACCAAGGAGGTGGTGAG
aldh1a3.L	TAAAGCCCTGTCTGTTTCT	CATACTCTCCAAGTTCCCTT
crabp2.L	AGCCACCCAAAGAAGACATAC	CGATAAGAAACGAAAGCAGAAA
crabp2.S	TCAAAGGAGATGGACCCAAGA	ATCAGCAGTCATGGTCAGGATAAG
cyp26a1.L	TCGAGGTTCGGCTTCATC	CGGCACAATTCCACAACA
cyp26a1.S	CCGCTTTCTAACGCCACTT	CACAATTCCACCACGAACAC
cyp26c1.S	AGCTCTGGTCCTTGAGATGG	AGCCAATGCAGAGTTTCTCC
dhrs3.L	CAGGCGCAAGAAATCCTAAG	CAAAGGCCACGTTACAGGAT
hoxa1.L	CCGCTCACTATATCCACCATTC	TGGCAGGAGAACGACAAAC
hoxa1.S	AATTATGAGATGATGGAATGGTAAA	TGACTGTAAACACCTAGTAAATGAGAG
hoxa3.S	AGCAGGGCAATGGAGTTT	GGAGGGTCCACCAGAATTAG
hoxb4.S	CCAAGGATCTGTGCGTCAA	GCAGGATGGAGGCGAACT
hoxd3.S	CTTCCCAGTCCACAATGAATAAA	GCTCTTCTCCTCGCAGTTCTC
rdh10.L	CGTCTCTTTGCCCTGGAGTTT	CACCATCTCCGCCGTCTC
rdh10.S	TTGCTTGGCCTGTAGAAGAGA	TGCATGGCGAAATAGGAGTAG
sdr16c5.L	TTTGTGGTTCCTTCCCTCTC	GTGCCATCAGTCTCCCTATACC
stra6.L	CCTGCTTACTTTCCTCCTGTTG	GTGGGTGACATTAAAGATTGTAGAGA
gapdh	GCTCCTCTCGCAAAGGTCAT	GGGCCATCCACTGTCTTCTG

Supplemental Table S3. RA network component polymorphisms between *Xenopus* strains[1]

Gene name	***Gene ID***	***aa position***	***aa1***	***aa2***
aldh1a2	18020673m	240	P	S
cyp26c1	18034595m	388	F	I
rbp1	18027898m	26	T	I
rbp1	18027898m	149	E	K
rbp1	18027898m	27	H	R
rdh10	18033799m	133	H	R
rdh13	18026677m	14	C	F
sdr16c5	18032037m	35	A	T
stra6	18018036m	610	S	N

[1]based on (Savova et al., 2017)

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Figure 1

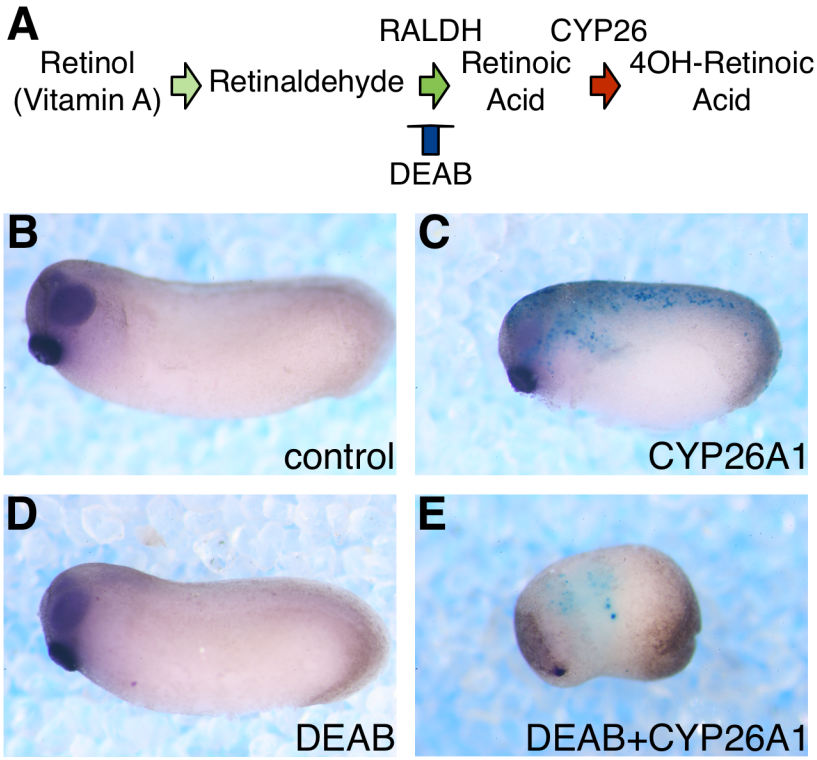

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Figure 2

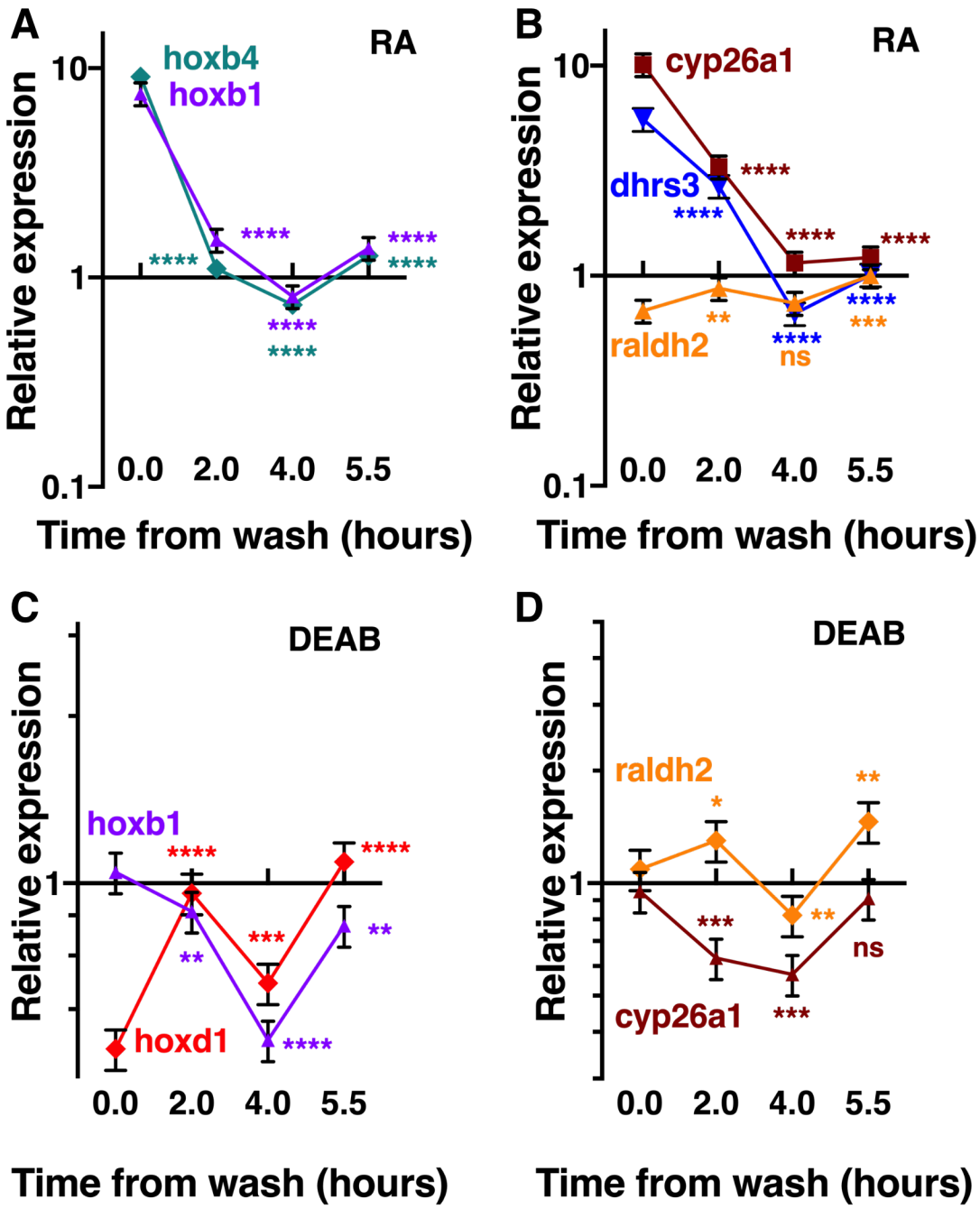

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Figure 3

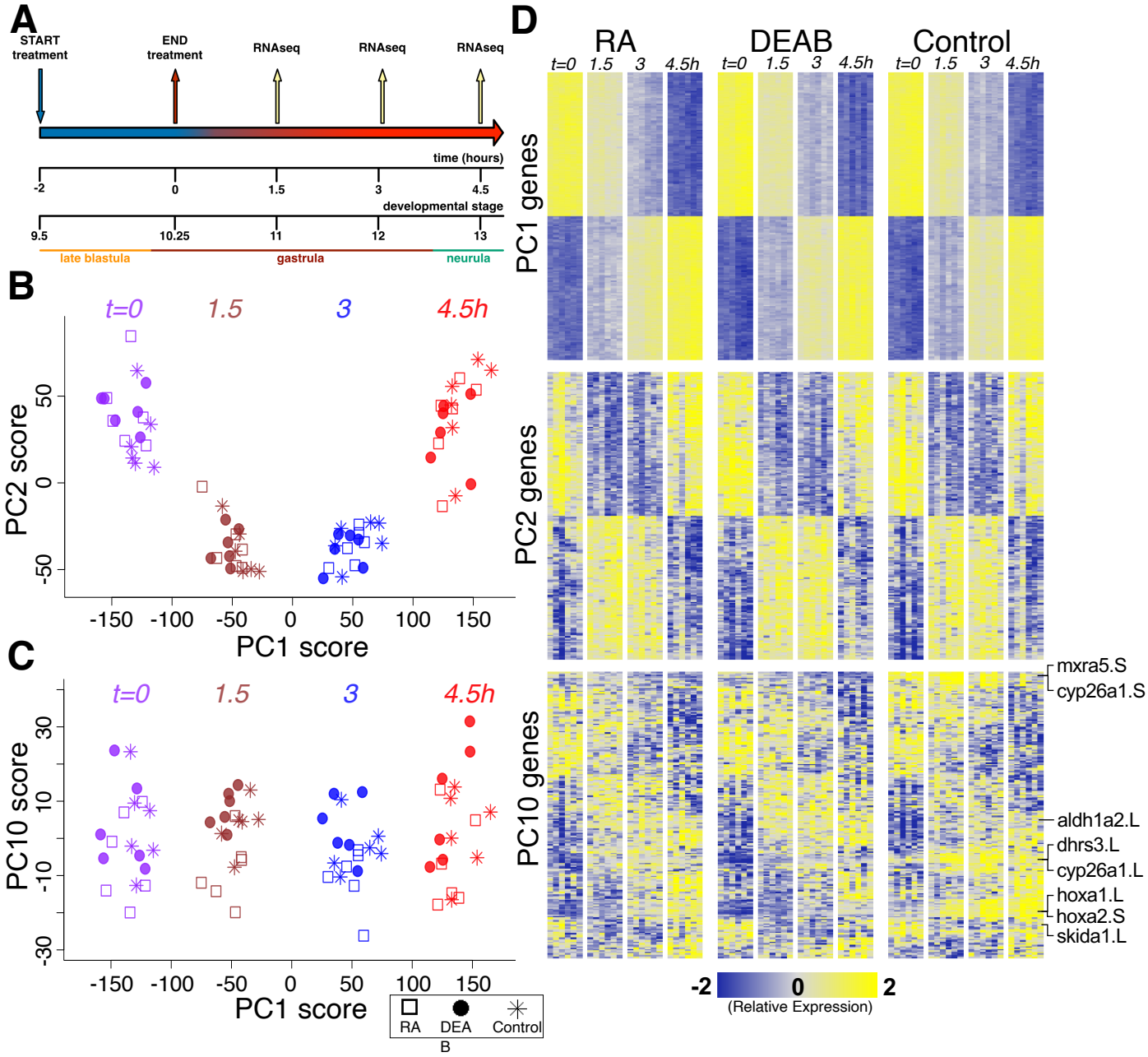

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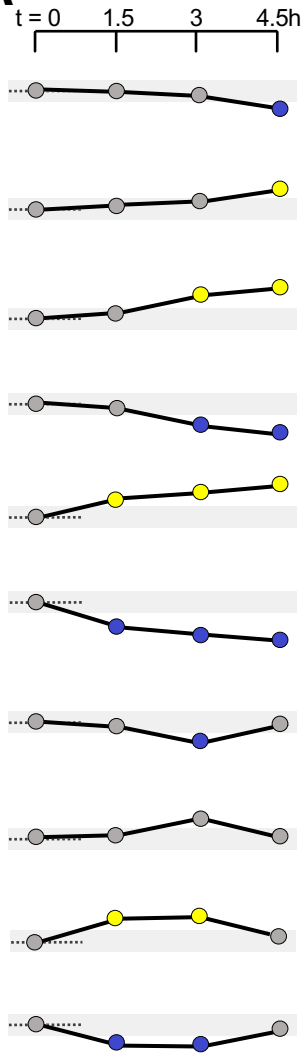
Figure 4

A



RA	DEAB	Control
1074	1115	1175
867	945	952
1013	975	937
842	811	753
218	227	193
86	91	53
58	38	37
23	27	18
4	4	2
1	1	1

B

Enriched Processes

carboxylic acid metabolism / autophagy / lipid transport / localization / development / cell cycle

translation / peptide biosynthesis / demethylation / tissue migration / signaling

development / adhesion / transcription / defense response / localization

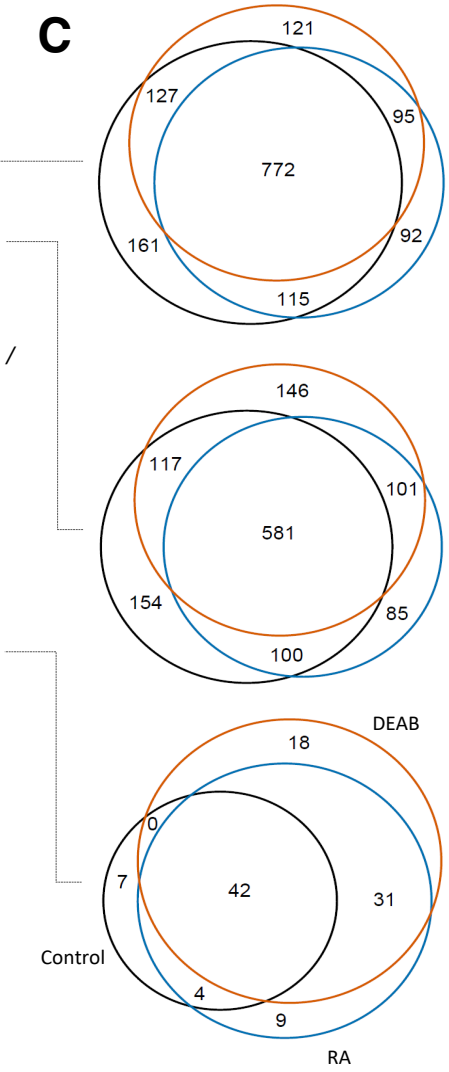
signal transduction / protein phosphorylation / cell cycle / cytoskeleton organization / ATP generation / autophagy / DNA repair

development / transcription / cell signaling / adhesion / immune system / RA biosynthesis

morphogenesis / gastrulation / protein phosphorylation

centrosome separation / nuclear division

C



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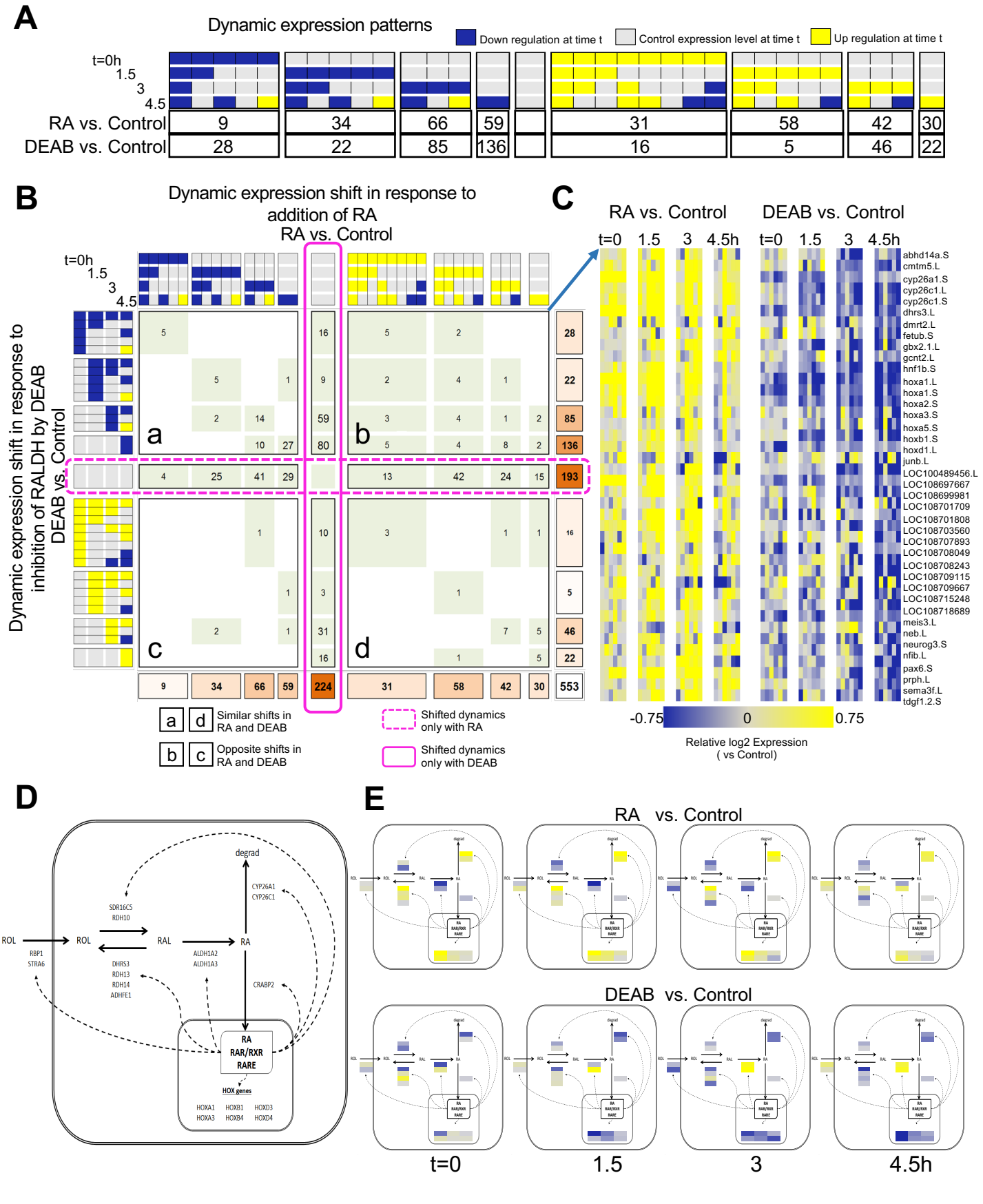

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Figure 6

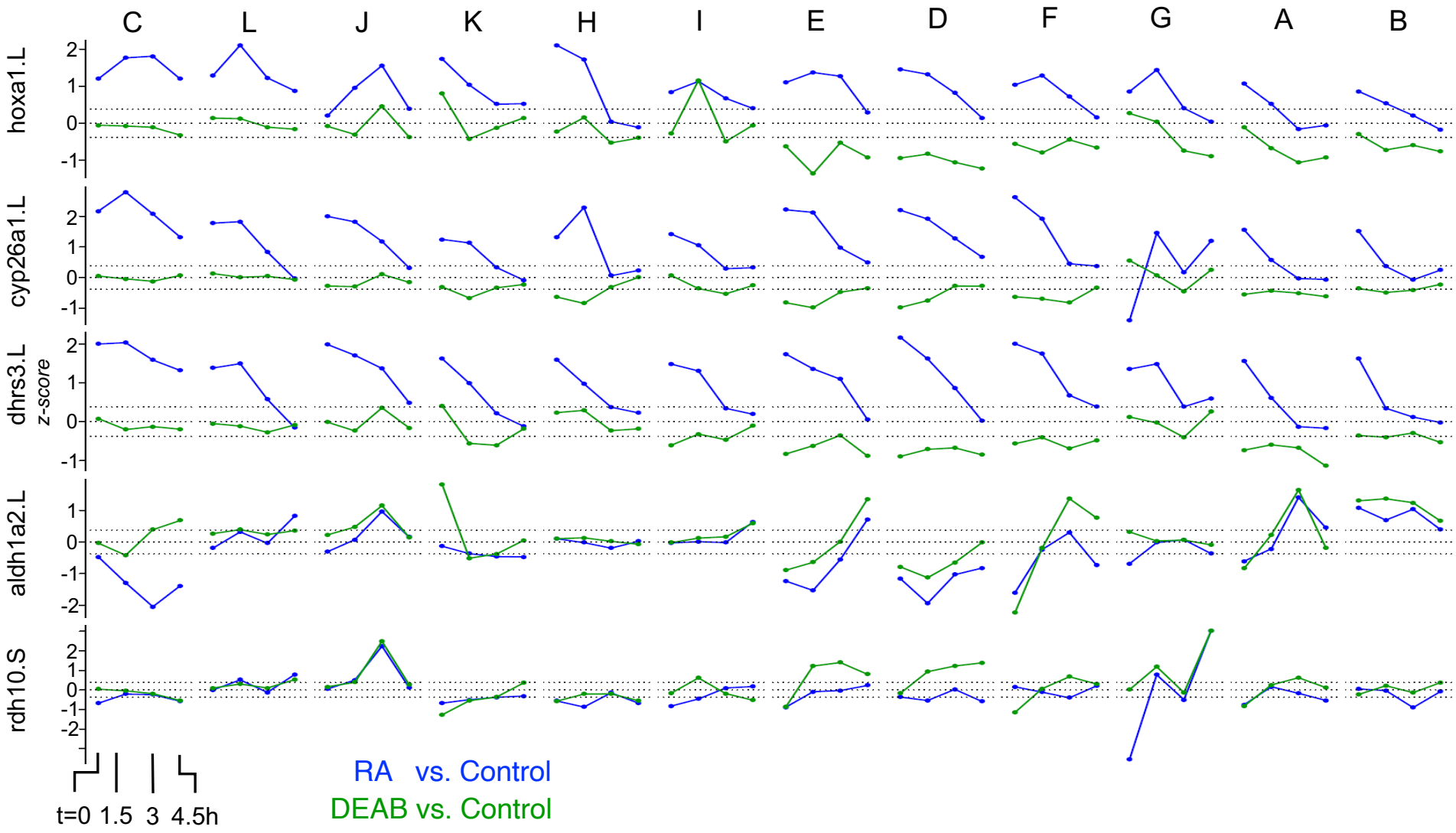

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Figure 7

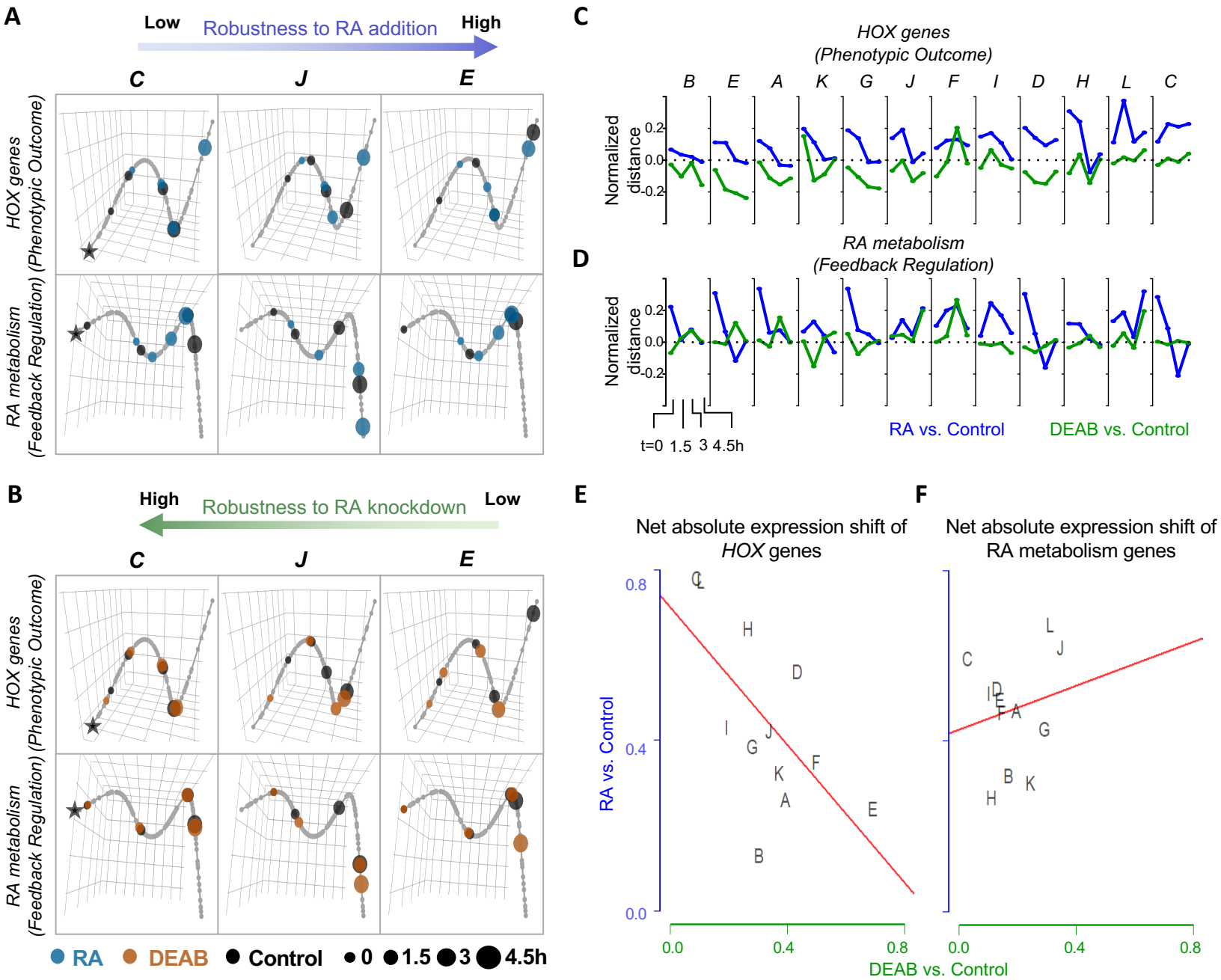

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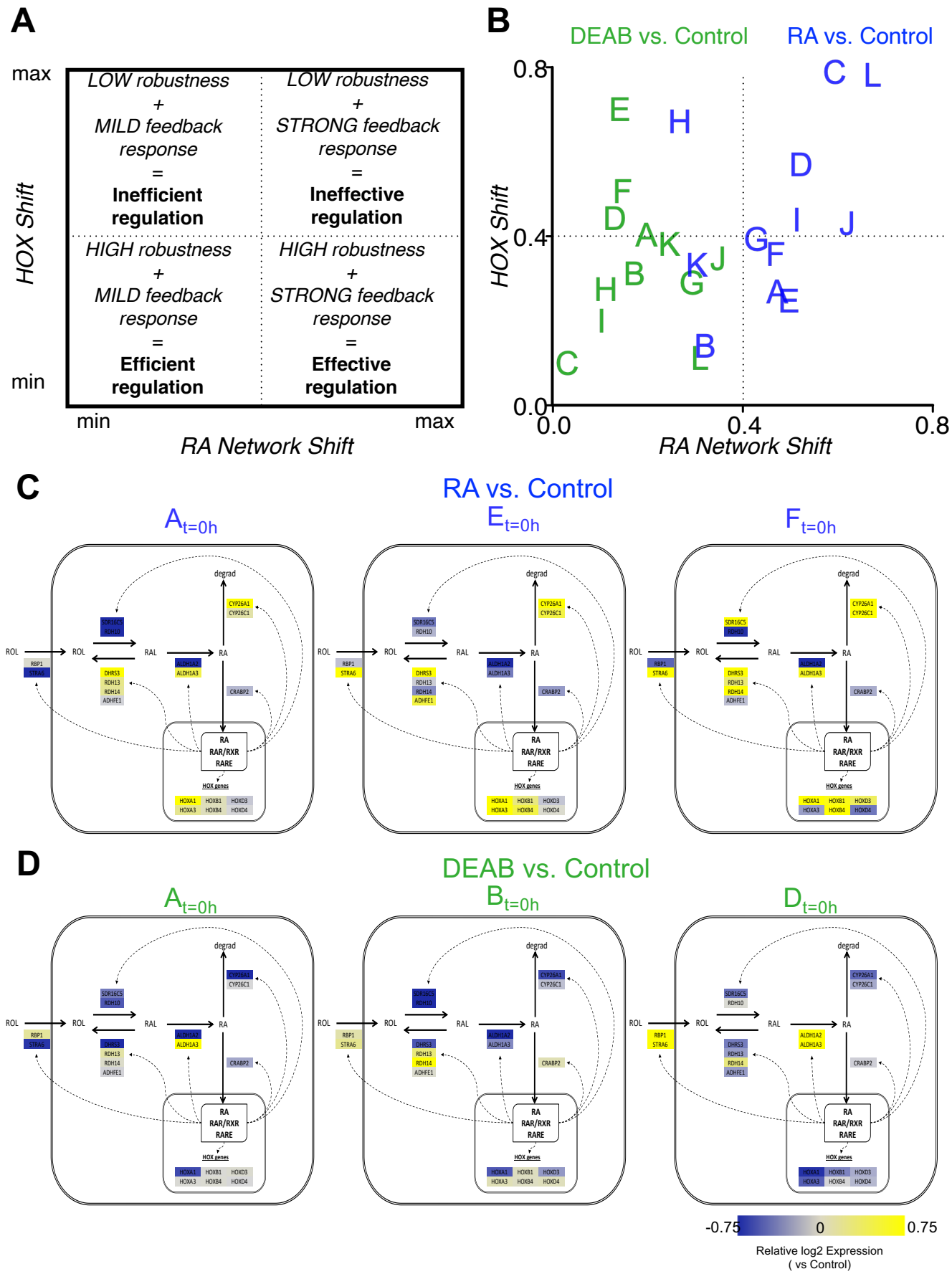
Figure 8



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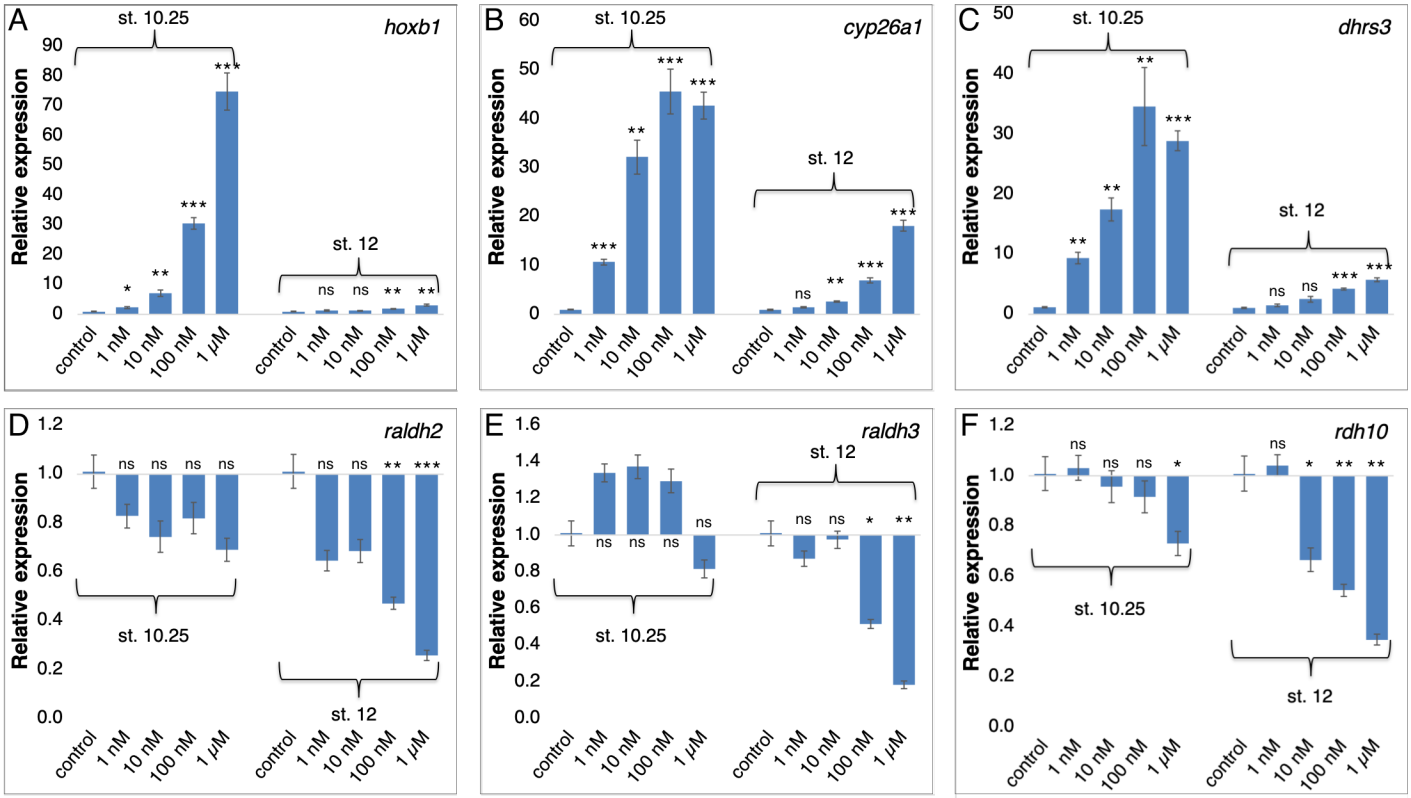
Supplemental Figure S1



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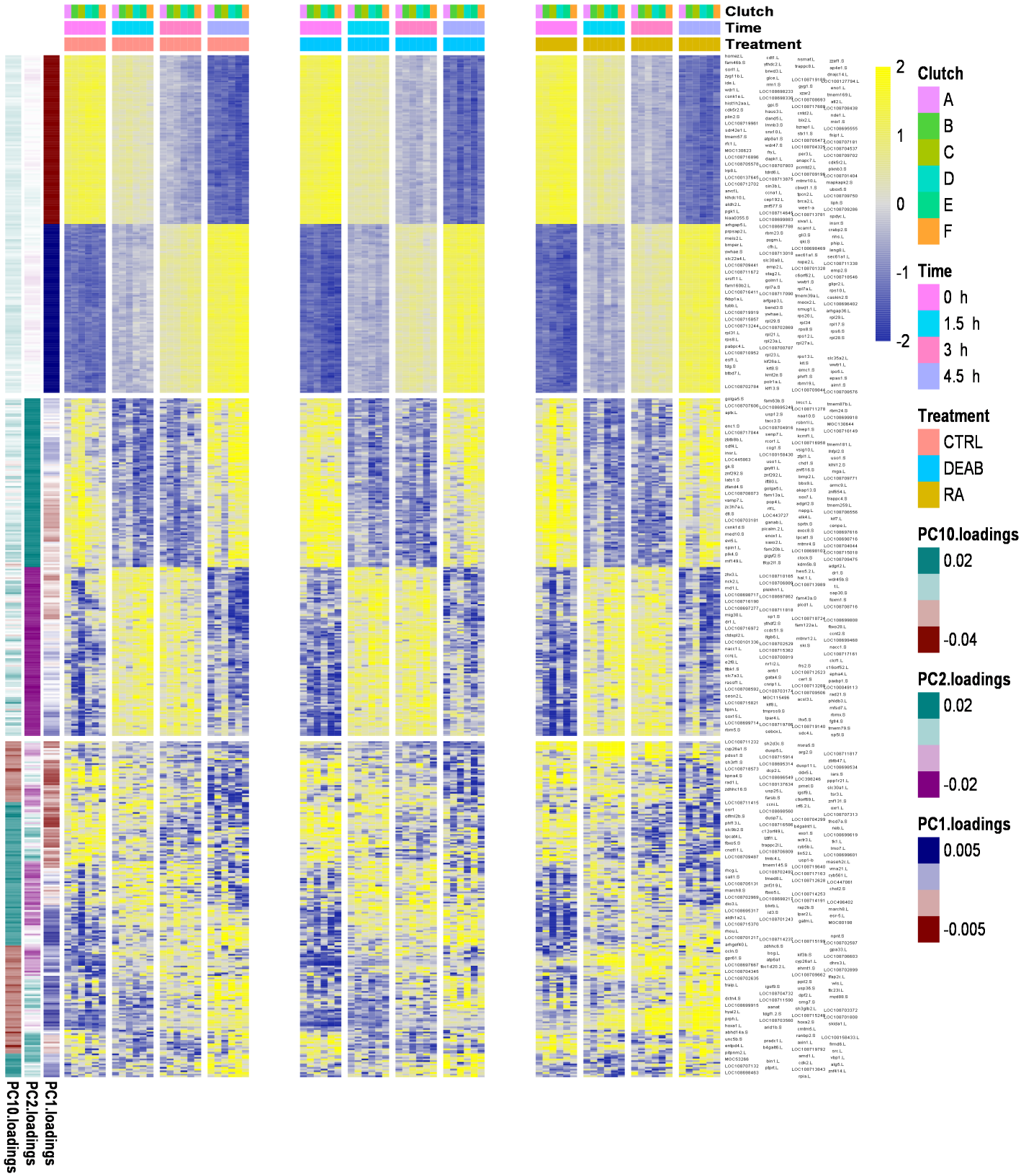

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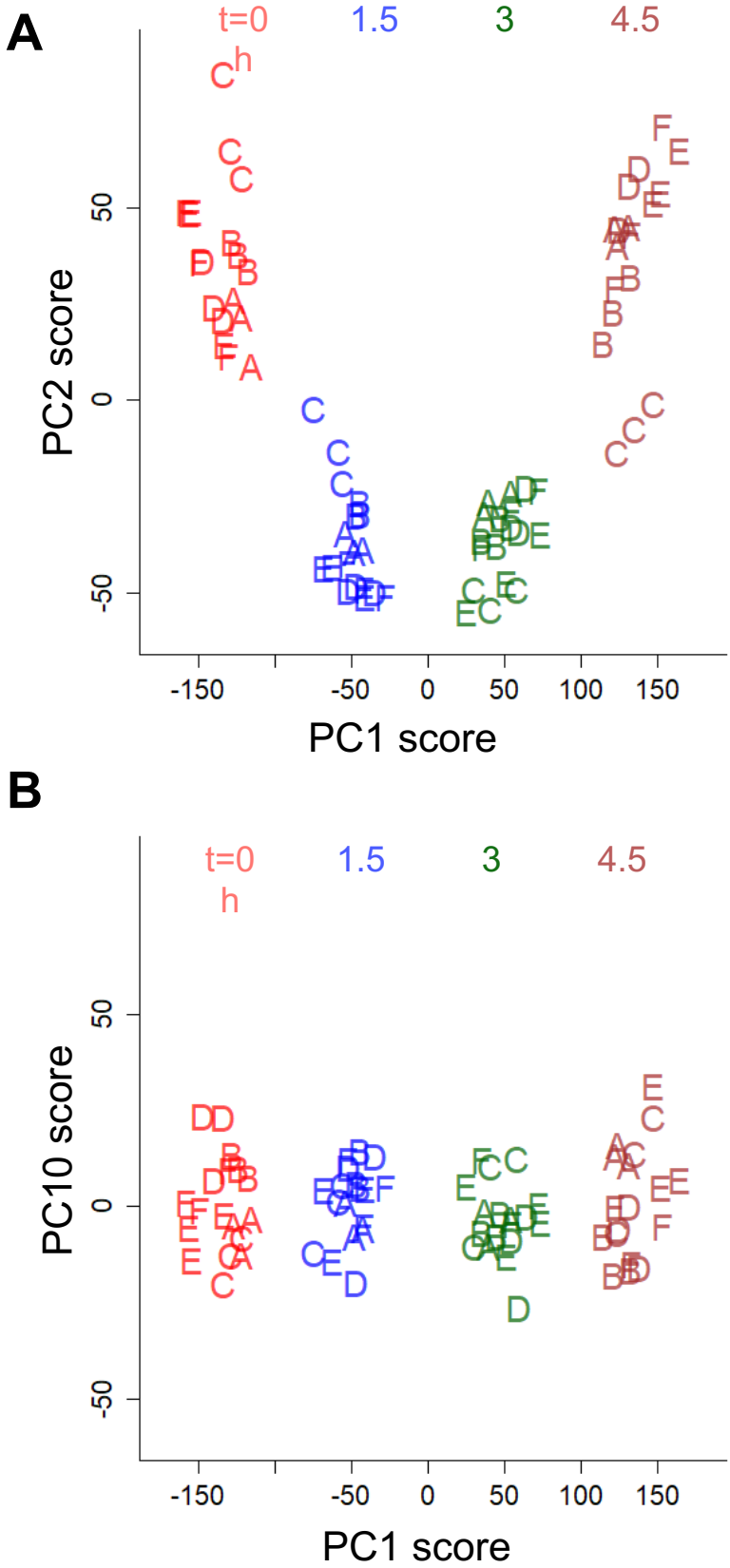
Supplemental Figure S3



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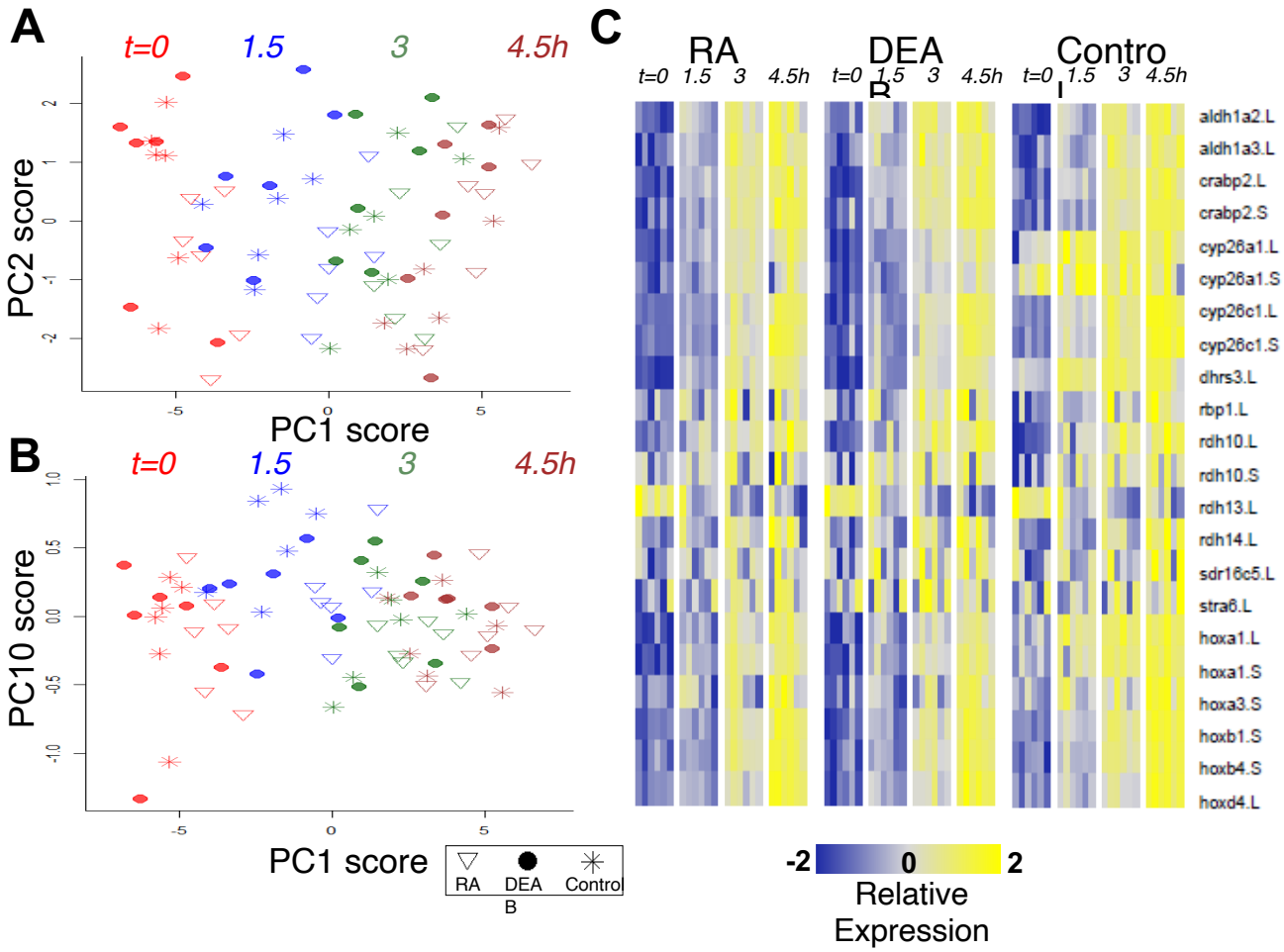
Supplemental Figure S4



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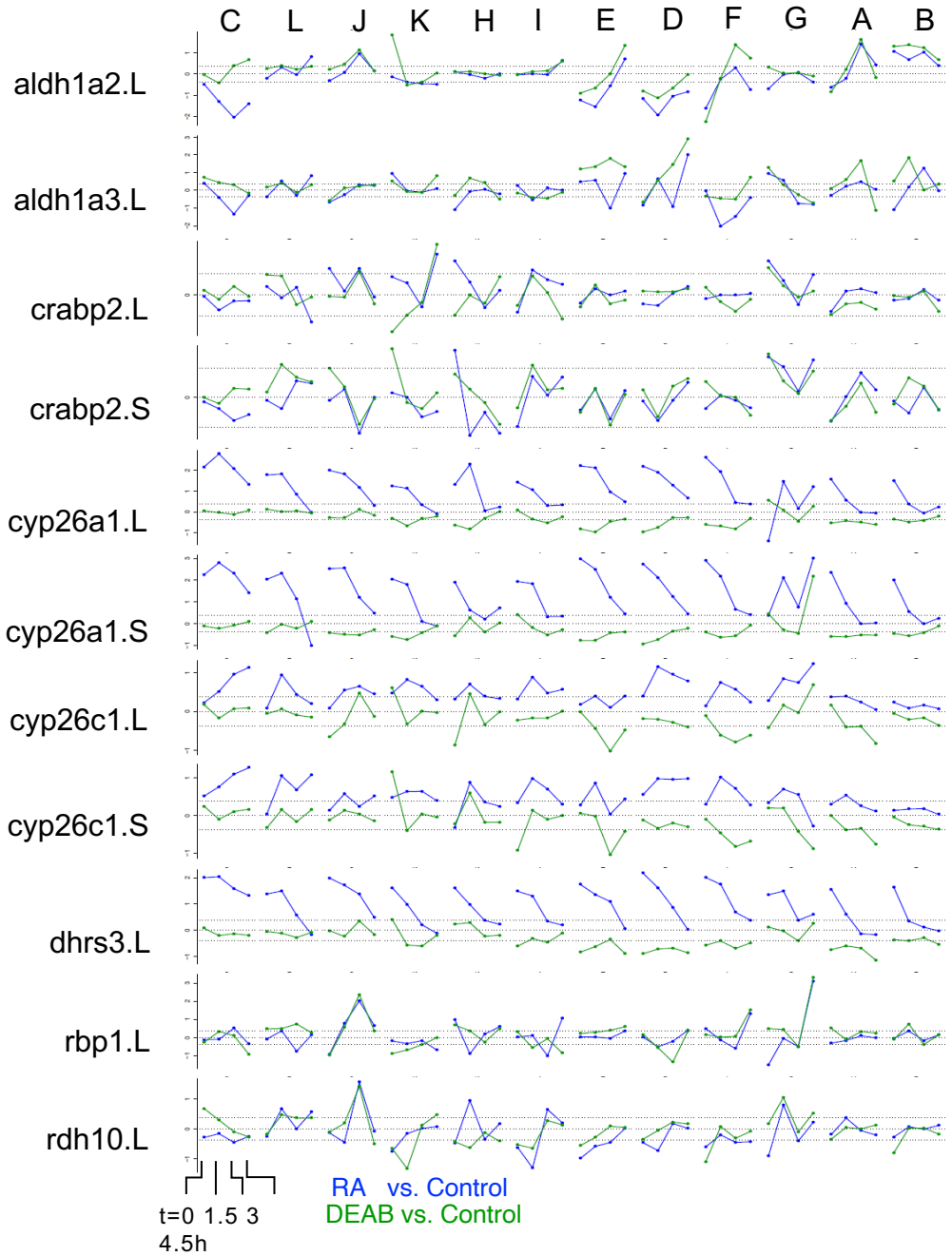
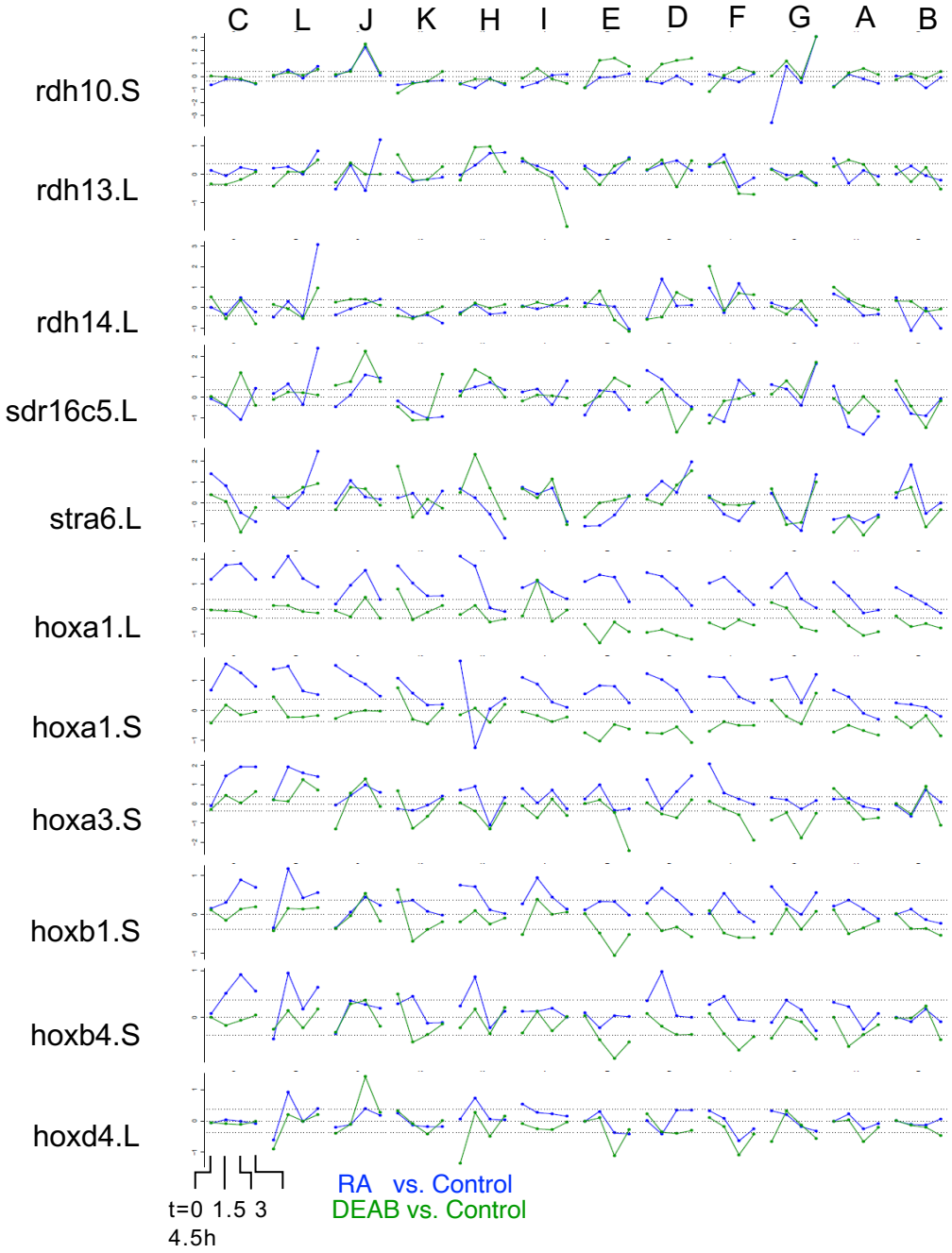
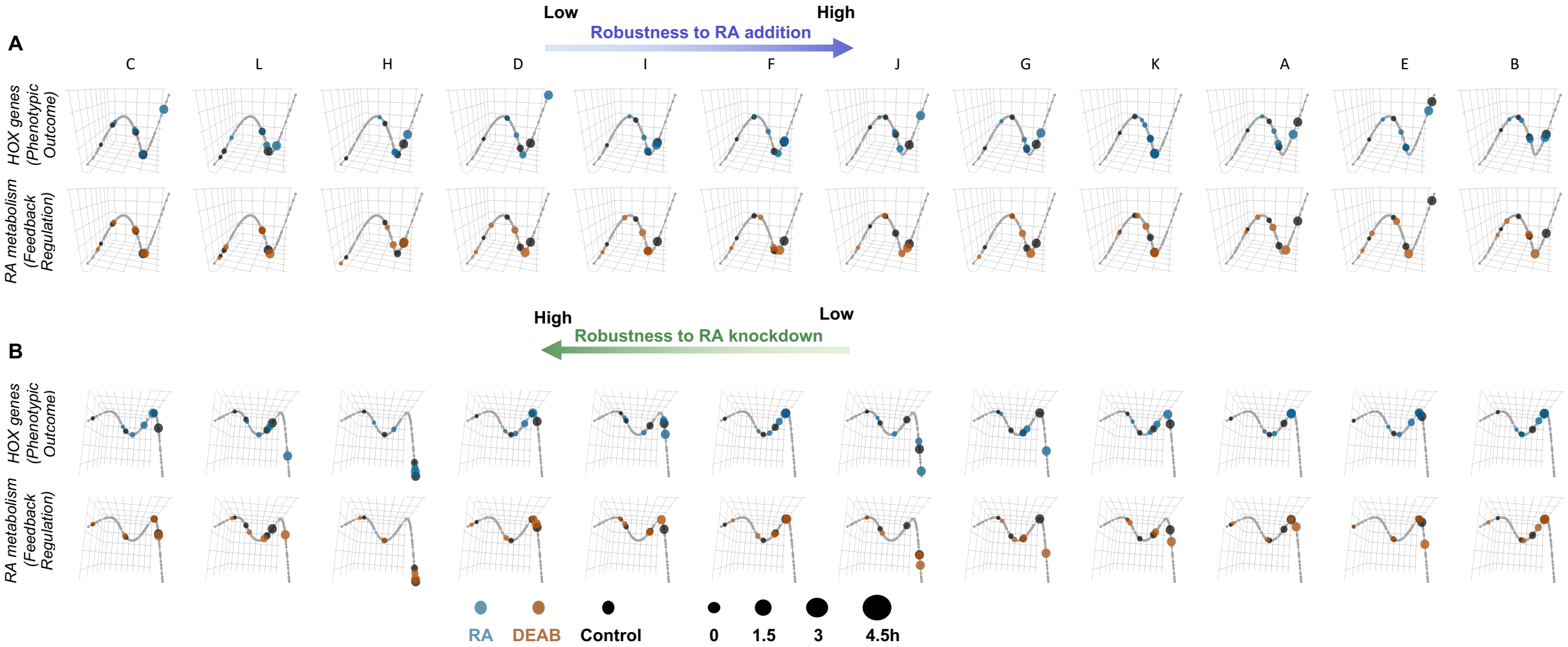
Supplemental Figure S5

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Supplemental Figure S6