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Modular Evolution of DNA-Binding Preference of a Tbrain Transcription Factor Provides a Mechanism for Modifying Gene Regulatory Networks

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Abstract

Gene regulatory networks (GRNs) describe the progression of transcriptional states that take a single-celled zygote to a multicellular organism. It is well documented that GRNs can evolve extensively through mutations to cis-regulatory modules (CRMs). Transcription factor proteins that bind these CRMs may also evolve to produce novelty. Coding changes are considered to be rarer, however, because transcription factors are multifunctional and hence are more constrained to evolve in ways that will not produce widespread detrimental effects. Recent technological advances have unearthed a surprising variation in DNA-binding abilities, such that individual transcription factors may recognize both a preferred primary motif and an additional secondary motif. This provides a source of modularity in function. Here, we demonstrate that orthologous transcription factors can also evolve a changed preference for a secondary binding motif, thereby offering an unexplored mechanism for GRN evolution. Using protein-binding microarray, surface plasmon resonance, and in vivo reporter assays, we demonstrate an important difference in DNA-binding preference between Tbrain protein orthologs in two species of echinoderms, the sea star, Patiria miniata, and the sea urchin, Strongylocentrotus purpuratus. Although both orthologs recognize the same primary motif, only the sea star Tbr also has a secondary binding motif. Our in vivo assays demonstrate that this difference may allow for greater evolutionary change in timing of regulatory control. This uncovers a layer of transcription factor binding divergence that could exist for many pairs of orthologs. We hypothesize that this divergence provides modularity that allows orthologous transcription factors to evolve novel roles in GRNs through modification of binding to secondary sites.

Key words: evo-devo, gene regulatory networks, transcription factors, echinoderm, evolution, T-box.

Introduction

Animal morphology arises under the control of interacting networks of regulatory genes that operate during embryonic development. A central pursuit for understanding evolution of animal form is therefore to determine how these gene regulatory networks (GRNs) evolve. Several influential articles, published almost 50 years ago, set forth the hypothesis that noncoding DNA, that is, the cis regulatory DNA, would be the predominant source of evolutionary change. This idea was first predicted by Monod and Jacob (1961) who emphasized the important distinction between biochemical protein function and context of the action of that protein. Britten and Davidson (1971) established the hypothesis that regulatory mutations, which control this context, would be the prominent source of evolutionary variation. In 1975, King and Wilson suggested that the stark differences in morphology and behavior between chimpanzees and humans, despite their overall high similarity in DNA sequence, could be the result of differences in their regulatory DNA. These, and other articles of this era, firmly established the notion that changes to the deployment of genes, rather than the biochemical function of genes would be the main driver in morphological diversity. The rationale for this is theoretically straightforward. A single gene is usually regulated by multiple cis-regulatory modules (CRMs; and also referred to as enhancers), so that its expression in distinct spatial and temporal domains is governed independently. By comparison, the transcription factors that utilize these CRMs must remain evolutionarily dormant because they often are needed to orchestrate a variety of crucial tasks. This tends to be especially evident during development where transcriptions factors are used in multiple contexts. It stands to reason that mutations to CRMs have fewer pleiotropic effects and are therefore more likely to pass the filter of selection and thus these become the source of novelty and change (reviewed in Carroll 2005; Prud’homme et al. 2007; Wray 2007).

Many early discoveries in evolutionary developmental biology supported this hypothesis. A wealth of data
demonstrates that all animals share highly similar sets of regulatory genes, which have been dubbed the toolkit for development (Carroll 2005). Regulatory genes comprise a relatively small portion of the transcriptome and hence must be used in many tissues and times in the developing embryo. Elegant xeno-transfer experiments further cemented the idea that regulatory proteins were evolutionarily dormant (McGinnis et al. 1999; Wang et al. 2002, 2004). One of the most exciting of these was the demonstration that the mouse pax6 gene could rescue the mutant phenotypes of the eyes absent ortholog in Drosophila and had therefore presumably changed very little in the 900 My (Hedges et al. 2006) since insects and vertebrates last shared a common pax6 gene (Halder et al. 1995).

More recently, a growing body of evidence suggests that although transcription factors may be a less common source of GRN evolutionary change, they are certainly not unchanging. Although transcription factors may be a less common source of GRN evolutionary change, they are certainly not unchanging (Lynch et al. 2011). Importantly, this acquisition seems to have a modular component to it. Some forkhead families can bind both the primary and secondary motif as well as an additional novel motif, whereas others bind to either the primary and secondary or only to novel motifs. It is unknown whether this phenomenon extends to other transcription factor families and the functional consequences of this change.

Recently, protein-binding microarray technology has revealed that the forkhead family of transcription factors can acquire novel binding specificity among both orthologs and paralogs (Nakagawa et al. 2013). Importantly, this acquisition seems to have a modular component to it. Some forkhead families can bind both the primary and secondary motif as well as an additional novel motif, whereas others bind to either the primary and secondary or only to novel motifs. It is unknown whether this phenomenon extends to other transcription factor families and the functional consequences of this change.

Here, we investigate orthologous Tbrain (Tbr) transcription factors from the sea star, Pariotia miniata (Pm), and sea urchin, Strongylocentrotus purpuratus (Sp), to question whether these proteins evolved biochemical changes in their DNA-binding preferences. These proteins were selected as they have well characterized and critical roles in early echinoderm development (Ryan et al. 1998; Shoguchi et al. 2000; Croce et al. 2001; Tagawa et al. 2001; Fuchikami et al. 2002; Horton and Gibson-Brown 2002; Oliveri et al. 2002; Hinman, Nguyen, Cameron, et al. 2003). During sea star embryogenesis, Tbr is highly pleiotropic and required for specification of cell types within the mesoderm, endoderm, and ectoderm (Hinman and Davidson 2007; McCauley et al. 2010). In sea urchins, intriguingly, Tbr appears to have lost these roles and is instead only required for the specification of one type of mesoderm, the skeletogenic mesoderm. These genes are members of the T-box family of transcription factors, which are characterized by having a single T-box DNA-binding domain. The DNA-binding properties of these proteins are relatively well studied. There is a particular interest in understanding how groups of T-boxes with the same primary binding motif, expressed in the same tissue, are capable of exerting distinct functions. Many studies show that these transcription factors are characteristically dose dependent, and others suggest that differences in binding site affinities may be crucial for allowing them to operate in a competitive and hierarchical fashion (Macindoe et al. 2009; Sakabe et al. 2012). Therefore, there is a great interest in understanding the binding properties of these transcription factors.

The echinoderm Tbr proteins are orthologous to vertebrate Eomesoderm (Eomes) (also known as Tbr2), Tbr1, and Tbx21 (Papaioannou and Silver 1998; Croce et al. 2001). As is the case for many vertebrate transcription factors,
these paralogs presumably arose as a result of the vertebrate lineage-specific duplication from a single deuterostome ortholog. We show that these three deuterostome orthologs (sea urchin Tbr, sea star Tbr, and mouse Eomes) have a highly similar primary binding motif, which we think has therefore been maintained in the approximately 800 My (Hedges et al. 2006) since these taxa last shared a common ancestor. Here, we show that, the sea star Tbr and mouse Eomes each have a preference for an additional, unique secondary motif; whereas the sea urchin Tbr protein has no preference for a secondary motif. This demonstrates that these orthologs evolved biochemical changes in function of their DNA-binding domains. We show that at saturating levels of Tbr, the primary and secondary motifs are functionally interchangeable in sea stars. The motifs, however, provide different transcriptional responses as Tbr protein levels change. The use of primary and secondary motifs represents a modular component to transcriptional regulation; subsets of target genes under control of secondary motifs can evolve, whereas those regulated by primary motifs remain conserved. Our data indicate that this evolvable function can manifest as differences in relative timing in response to transcriptional state changes. Given the pervasiveness of secondary binding ability among transcription factors, such changes in secondary binding may prove to be an important source of gene regulatory evolutionary change.

**Results**

**Sea Urchin and Sea Star Tbr Are Orthologous to Mouse Eomes**

In the sea star, *P. miniata*, tbrain (*PmTbr*) was originally isolated from a cDNA library probed with a cDNA clone corresponding to another T-box factor, *PmBrachyury* (*PmBra*) (Hinman, Nguyen, Cameron, et al. 2003). Only *bra* and a single *tbr* ortholog were identified in this screen. To determine whether any other *tbr* orthologs were present within the genome, we bioinformatically queried the *P. miniata* genome sequence (contigs 1.0; Echinobase.org, last accessed July 18, 2014) (Cameron et al. 2009) by performing a tBLASTn identity search to the translated *MmEomes* T-box domain (accession: AK089817.1). We collated the *P. miniata* sequences that matched with an e value less than 1e-12. These sequences in turn were used to query the National Center for Biotechnology Information nonredundant protein database using BLASTx (Altschul et al. 1990). Four T-box family members were identified in this comprehensive search. These correspond to a subset of the six T-box family members identified previously in the sea urchin, *S. purpuratus*, genome (Howard-Ashby et al. 2006). We next determined the orthology of these four T-box factors by constructing a gene tree (see Materials and Methods) of these T-boxes and their homologs from other deuterostome animals (fig. 1A).

*PmTbr* clusters with a *tbr* gene isolated from another species of sea star (*P. pectinifera*, *PpTbr*), whereas the *SpTbr* clusters with *tbr* orthologs from five other species of sea urchins, including two species of sand dollars, which form a distinct group (Irregularia) within the sea urchins. Importantly, the sea urchin and sea star genes form a single grouping supported by a posterior probability of 0.99. Thus, there is a strong correspondence between the topology of this gene tree and the echinoderm species tree (Pisani et al. 2012). In vertebrates, there are three *tbr* paralogs, namely *eomes, tbx21*, and *tbr1*, which also form a single grouping. These three paralogs form a single cluster with the echinoderm orthologs with the node connecting them supported by a posterior probability of 0.97.

Meanwhile, the other T-box proteins isolated in the screen are orthologous to *bra, tbx2/3*, and *tbx4*. Only a single *tbr* ortholog is identified from eight species of echinoderms, including two with sequenced genomes. Therefore, we are confident as reasonably possible that there is a single *tbr* ortholog among these echinoderms and that it is the only echinoderm ortholog of the vertebrate *eomes, tbx21*, and *tbr1* paralogs.

**Sea Urchin and Sea Star Tbr Orthologs Have Different DNA-Binding Preferences**

The structure and function of transcription factors, especially the DNA-binding domains, are often highly conserved across even widely divergent species. The 180 amino acid T-box domain is particularly well conserved (Macindoe et al. 2009). An alignment of the *SpTbr* and *PmTbr* DNA-binding domains demonstrate that they are 73% identical and 89% similar (fig. 1B). This indicates that these orthologs share high degree of conservation, yet there is variation that could permit functional divergence. We wanted to determine if any of these differences could indeed have a functional consequence. As a first approach, we used the known crystal structure of a closely related T-box protein, *Xenopus laevis* brachyury (*XbBra*) (Protein Data Bank ID 1XBR) (Müller and Herrmann 1997) to map the likely DNA contacts within the sea star and sea urchin Tbr amino acid sequences. We also used these sequences to predict the structures of *PmTbr* and *SpTbr* using the Phyre server (Kelley and Sternberg 2009). The overall structure of the DNA-binding domain is not predicted to be perturbed by the nonidentical amino acids (supplementary fig. 2A, Supplementary Material online). Nineteen amino acids are predicted to contact the DNA (highlighted in yellow in fig. 1B), and of these, two are not identical between the sea urchin and sea star (blue highlight, fig. 1B). At residue 338/428, the *SpTbr* protein has a glutamine where *PmTbr* has a serine. This appears to be unique for each species as neither is conserved with the residue in *XbBra* nor *MmEomes* (fig. 1B, supplementary fig. S1, Supplementary Material online). However, at residue 389/479, *PmTbr* has an asparagine that is also present in vertebrate proteins, whereas *SpTbr* has a histidine at this position. Both of these changes occur in residues known to interact with the DNA backbone as opposed to the bases themselves (supplementary fig. S2 and C, Supplementary Material online). However, in the case of the homeodomain protein, Bicoid, a change in DNA-binding specificity compared with its Antp paralog is correlated with a single backbone-contacting amino acid difference (Hanes and Brent 1989), and so these two changes to Tbr may also impact DNA-binding specificity.
**Fig. 1.** Sequence alignment for *Pm* and *SpTbr* T-box-DNA-binding domains. (A) Tree topology was determined using a MrBayes model (TOPALI v2.5) and is based on a character alignment that includes the T-box sequences depicted in supplementary figure S1, Supplementary Material online. Lengths (continued)
Although suggestive of a potential for a functional difference, protein–DNA interactions are not well understood enough to predict binding preferences. Therefore, it is unclear how these changes and others that do not occur in amino acids that contact DNA might affect specificity for DNA sequences. We therefore sought to determine experimentally if any differences in DNA specificity exist for these orthologs. We bacterially expressed and purified PmTbr and SpTbr DNA-binding domains as GST-fusion proteins and used protein-binding microarrays to universally assess their binding preferences (Berger et al. 2006; Berger and Bulyk 2009). It is important to note that these experiments cannot account for the effects that cofactors normally encountered in vivo might have on Tbr DNA-binding specificity. We chose to test only DNA-binding domains because full-length proteins prove to be extremely unstable. In a previously reported study, no difference in DNA binding was observed when full-length and DNA-binding domain versions of MmTbx5 were compared (Macindoe et al. 2009). Moreover, T-box protein specificity for several homologs, including MmEomes, has previously been shown to reside in the T-box domain itself, whereas other regions of the protein account for nucleo-localization signals and transactivation domains (Conlon et al. 2001). This work suggested that the Tbr DNA-binding domains would be sufficient to capture the full DNA-binding capabilities of these proteins.

Polymerase chain reaction (PCR)-based methods, such as SELEX, have been used to identify consensus sites for other T-box transcription factors (Conlon et al. 2001; Macindoe et al. 2009). However, these experiments, based on technologies available at the time, were limited to identifying only the highest affinity binding motifs. Protein-binding microarrays uncover additional layers of binding specificity, particularly differences in secondary sequence preferences (Badis et al. 2009).

The DNA-binding specificity of each Tbr was assayed by protein-binding microarray in duplicate with strong agreement between replicates (PmTbr Pearson’s $r = 0.915$ and SpTbr Pearson’s $r = 0.917$). Data sets depicting the $E$ score calculated for each 8-mer are available in supplementary table S1, Supplementary Material online. The protein-binding microarray experiments demonstrate that PmTbr and SpTbr orthologs recognize the same primary position weight matrix, or motif, which represents the probability of the transcription factor binding to all potential binding sites (fig. 2A and C). This motif can explain Tbr binding to a large number of 8-mer-binding sites, but for simplicity, it can be represented by the following consensus sequence, 5’-AGGTGTA-3’. This single binding site was selected for use in subsequent experiments because each position contains the most highly preferred nucleotide predicted by the position weight matrix. Both Tbr orthologs recognize this 8-mer-binding site with a very high $E$ score (PmTbr, $E = 0.499$, SpTbr, $E = 0.498$). The $E$ score (enrichment score) is a nonparametric, modified Wilcoxon–Mann–Whitney statistic developed especially to measure relative binding preference for simple and robust comparison of protein-binding microarray data across data sets (Berger et al. 2006). $E$ scores range from −0.5 to 0.5, but scores of 0.45 and greater indicate a stringent binding threshold (Berger et al. 2008; Badis et al. 2009). This motif closely matches previously published T-box consensus sites (Conlon et al. 2001; Macindoe et al. 2009), and in particular, the primary binding site for the mouse ortholog of Tbr, MmEomes ($E = 0.497$, UniProbe Database), which was also obtained by universal protein-binding microarrays (Badis et al. 2009).

Previous studies using these sensitive protein-binding arrays have shown that approximately 40% of transcription factors that have been tested can bind two distinct motifs (Badis et al. 2009; Gordân et al. 2011). By convention, the motif with the higher seed $E$ score is called the primary motif and the next preferred, high confidence motif, the secondary motif. Of our two echinoderm Tbr orthologs, only PmTbr, however, consistently recognized an additional high $E$-score position weight matrix, best represented by the 8-mer, 5’-AGGTGACA-3’ ($E = 0.483$) (fig. 2B, supplementary table S1, Supplementary Material online). Although very similar to the initial motif, it differs in positions 13 and 14, where AC replaces the primary site’s TG. Therefore, here we call the position weight matrix represented by the 8-mer 5’-AGGTGTA-3’ the primary motif and that represented by 5’-AGGTGACA-3’, the secondary. These two motifs are not condensed into one more degenerate position weight matrix, because the two distinct motifs better explain the protein-binding microarray data than can a single motif (Badis et al. 2009). This secondary motif was found consistently in replicate experiments. In contrast, SpTbr never demonstrated strong preference for a particular additional motif (supplementary table S1, Supplementary Material online) over replicate experiments. When we performed a similar analysis using the data from SpTbr binding to find a secondary motif, the result was simply a more degenerate version of the primary motif. Additionally, we show that SpTbr and PmTbr have similar $E$ scores for 8-mers that match the primary position weight matrix, but 8-mers corresponding to the PmTbr secondary motif are preferred by PmTbr (fig. 2D).

The mouse Eomes ortholog also was previously shown to also have two high $E$-score motifs. Although both species of
**FIG. 2.** Position weight matrices depicting binding specificities of Tbr orthologs. Position weight matrices represent the top motifs obtained from PBM data using the Seed-and-Wobble algorithm (Berger et al. 2006; Berger and Bulyk 2009) representing SpTbr and PmTbr data set 1 (supplementary table S1, Supplementary Material online). Secondary motifs represent high-scoring oligomers whose specificity is not captured by the primary motif. Representative 8-mers and their E scores are provided underneath each motif. (A) PmTbr primary binding motif. (B) PmTbr secondary binding motif. (C) SpTbr primary motif. (D) Scatterplot of E scores for each 8-mer in the PmTbr versus the SpTbr data sets. The top 14 8-mer matches to the shared primary position weight matrix are indicated in red, whereas the top 14 matches to the PmTbr secondary motif are blue. All 8-mers and their reverse compliments (supplementary table S1, Supplementary Material online) were assigned sum probability scores based on how well they matched any 8 bp stretch of PmTbr primary position weight matrix (from positions 6–17 shown in A) and PmTbr secondary position weight matrix (from positions 7–18 shown in B). The 14 matches to each site are the top 0.02% of 8-mer matches ranked by sum probability score. E score values indicate the statistical confidence in the seed 8-mer used in position weight matrix construction, where $E > 0.45$ is considered to be a high-confidence binding event (Berger et al. 2006).
RU values were plotted versus protein concentration and fit to a 1:1 binding model (Adjusted were assayed with equal binding conditions. The equilibrium concentrations. Samples of Tbr from each species were taken at 95s into the association phase, where equilibrium response can be ascertained and used to calculate stable equilibrium is reached quickly, and, therefore, equilibrium response can be ascertained and used to calculate affinity.

To determine affinities, equilibrium response units (RUs) were taken at 95s into the association phase, where equilibrium is established, as indicated by the slope = 0 in the sensograms (fig. 3B). Such measurements were taken from sensograms corresponding to at least five, but as many as ten, concentrations. Samples of Tbr from each species were applied to the same SPR chip alternately so both proteins were assayed with equal binding conditions. The equilibrium RU values were plotted versus protein concentration and fit to a 1:1 binding model (Adjusted $R^2 > 0.99$) (fig. 3C and D). Averaged affinity results from four or more experiments across these protein concentrations are shown in figure 3E. PmTbr recognizes the primary motif slightly better than does SpTbr, with affinities of 107 ± 8 nM for PmTbr and 137 ± 7 nM for SpTbr. By comparison, PmTbr binds the secondary site with significantly greater affinity that does SpTbr. PmTbr binds the secondary site with an affinity of 446 ± 17 nM and SpTbr binds with an affinity of 989 ± 49 nM (two-tailed t-test, $t = 11.612$, df = 6, $P = 0.0007$) (fig. 3C and E). Neither echinoderm Tbr ortholog binds particularly well to the MmEomes secondary site; PmTbr binds with an affinity of 732 ± 10 nM and SpTbr with an affinity of 882 ± 153 nM (fig. 3D and E).

We also compared relative affinity of PmTbr and SpTbr for each secondary site versus affinity for the primary site (fig. 3F) by dividing their respective primary site $K_0$ by $K_0$S for all other binding sites. This allowed us to ascertain whether SpTbr’s lower affinity for the secondary site could be due to an overall reduction in binding affinity because even SpTbr’s affinity for the primary site is slightly lower than PmTbr’s. The relative affinity of the secondary site versus the primary site is 0.24 for PmTbr, whereas for SpTbr it is significantly lower at 0.14 (two-tailed t-test, $t = 8.944$, df = 6, $P = 0.0022$, Bonferroni corrected). SpTbr’s relative affinity for PmTbr’s secondary site is comparable to the relative affinity both Tbrs have for MmEomes’s secondary site (0.15 and 0.16). PmTbr clearly binds its own secondary site better than it binds the MmEomes secondary site (two-tailed t-test, $t = 8.165$, df = 4, $P = 0.0024$, Bonferroni corrected). It also has a stronger relative affinity for this site than SpTbr has for the secondary site from either PmTbr or MmEomes.

The data shown in figure 3 provide an independent confirmation of the protein-binding microarray data (fig. 2 and supplementary table S1, Supplementary Material online) with an additional quantification of sequence affinity. They show that PmTbr has a stronger preference for its secondary motif than does SpTbr in spite of the similar affinities these echinoderm proteins have for their primary motif and for the MmEomes secondary motif. Although SpTbr tends to bind all tested sites with slightly less affinity than does PmTbr, it is notable that this is not enough to explain the larger difference in binding observed for the PmTbr secondary site, as demonstrated by comparisons of relative affinity.

The Secondary Site Can Substitute for the Primary Site In Vivo When Tbr Levels Are High but Not When They Are Reduced

We next wanted to determine how the primary and secondary sites function in vivo to regulate transcription to understand whether these differences are biologically relevant. We had previously characterized a CRM (OtxG) that controls the expression of the sea star otx gene (Hinman et al. 2007) and contains a single endogenous Tbr site that is a perfect match to the protein-binding microarray-derived primary motif (fig. 4A). We first confirmed that Tbr binds directly to this CRM in vivo using chromatin immunoprecipitation (ChIP) PCR. ChIP was performed in embryos at 30 hours post-fertilization (h), a time point during which OtxG is known to be active (Hinman et al. 2007). We show that the genomic region containing OtxG is greatly enriched in chromatin pulled down by the anti-PmTbr antibody compared with input chromatin and mock ChIP chromatin (fig. 4B). Importantly, genomic regions 1 kb up or downstream of OtxG are not enriched in PmTbr ChIP DNA (fig. 4B).

We next produced a series of constructs to determine how the primary and secondary motifs would behave in vivo...
“Basal Promoter GFP” is a previously existing construct that contains only a basal promoter in a GFP expression vector (Hinman et al. 2007). This imparts very low levels of ubiquitous GFP expression. The “OtxG GFP” construct has the endogenous OtxG CRM added upstream of the basal promoter. “2°C Tbr GFP” has a 2-bp mutation which changes the endogenous primary motif to a secondary motif. “Tbr Deletion GFP” ablates the Tbr-binding site by changing the same bases mutated in “2°C Tbr GFP” but so that the resulting site is one that had an average E score of −0.058 in the protein-binding microarray data set. By comparison, our motifs selected to represent the primary and secondary position
weight matrices had average $E$ scores of 0.499 and 0.483, respectively. $PmTbr$ should, therefore, be unable to bind this site.

These constructs are injected into embryos where they express the reporter gene in clones of cells. In each experiment, our various GFP constructs are coinjected with OtxG mCherry, which is identical to OtxG GFP except that coding sequence for the mCherry gene replaces that of the GFP reporter. The OtxG mCherry construct is used to normalize each sample for differences in injection volume, mosaicism

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**Fig. 4.** $PmTbr$ can use the primary and secondary sites in vivo to drive reporter gene expression interchangeably except when Tbr levels are reduced. (A) Schematics depicting OtxG mCherry, OtxG GFP, 2′ Tbr GFP, Tbr Deletion GFP, and Basal promoter GFP reporter gene constructs including the endogenous and mutated Tbr-binding motifs of interest. (B) ChIP PCR using primers pairs surrounding OtxG (OtxG CRM Amplicon) or primers pairs 1 kb up or downstream of OtxG. EtBr-stained gel shows amplicons obtained from total chromatin, preimmune sera mock ChIP, and Anti-PmTbr ChIP. (C–E) qPCR analysis of GFP expression levels driven by constructs indicated. All GFP expression levels have been normalized to mCherry levels that were driven by the coinjected OtxG mCherry construct. (C) Normalized GFP expression levels of OtxG GFP, Basal Promoter GFP, and Tbr Deletion GFP at 28 h. (D) At developmental time points 21 h, 25 h, and 28 h, Tbr is equally able to drive expression from OtxG reporters containing an endogenous primary site and introduced secondary site. The normalized expression level of GFP in OtxG GFP (blue bars) compared with 2′ Tbr GFP (red bars) is not significantly different. (E) Normalized GFP expression levels resulting from 2′ Tbr GFP or OtxG GFP coinjected with control MASO (blue bars) or Tbr (red bars) MASOs. In panels, $n$ indicates the number of replicate samples, each consisting of 50 sibling embryos. All error bars indicate standard error of the mean. $P$ values indicate the results of a two-tailed $t$-test. Details of these tests are provided in the main text. NS indicates not significant by two-tailed $t$-test.
of reporter incorporation, and embryo collection and processing. We used mCherry rather than an endogenous housekeeping gene to normalize GFP expression levels as this reporter will also account for injection variation. We do expect that there may be some differences in overall GFP versus mCherry transcript levels driven by identical CRMs because these mRNA transcripts may have different stability in vivo. It is important to note, however, that none of our assays directly compares GFP to mCherry levels but instead compare GFP levels across assays at a single time point that have been normalized to mCherry. Therefore, absolute differences in coinjected reporter levels themselves will not affect our analyses.

We assayed the expression of these reporter genes using a combination of approaches. Quantitative reverse transcription PCR (qRT-PCR) was used to determine the abundance of the reporters relative to each other (fig. 4). Fluorescent whole-mount in situ hybridization (FISH) was used to examine the spatial localization of these reporters (fig. 5). We use FISH rather than assays for fluorescent protein localization, as RNA localization is a more direct measure of transcript regulation and should coincide with qRT-PCR. GFP and mCherry proteins are relatively stable and can persist within the embryo after gene expression is extinguished. We also quantified fluorescent signal strength in whole-mount FISH embryos using ImageJ (Schneider et al. 2012). This last approach allows us to specifically estimate the abundance of each reporter within a particular spatial location (fig. 5).

We first performed a series of controls to verify the utility of this reporter system. We confirmed that the Basal Promoter GFP construct does not drive significant expression on its own when coinjected with other constructs. Basal Promoter GFP drives expression at a roughly 10-fold lower level than OtxG GFP in sibling embryos of the same stage (28 hours post-fertilization (h)). This indicates that there is no cross-regulation between the OtxG mCherry construct used for normalization and the Basal Promoter GFP coinjected constructs (two-tailed t-test, \( t = 9.082, df = 12, P = 0.0002, \) Bonferroni corrected) (fig. 4C). Tbr Deletion GFP expression is also significantly reduced compared with OtxG GFP, indicating that the Tbr-binding site within OtxG is crucial for normal expression levels (two-tailed t-test, \( t = 3.305, df = 12, P = 0.011 \), Bonferroni corrected). Combined, these experiments establish that the validity of this reporter system for assaying primary and secondary site usage in vivo. They demonstrate that the basal promoter does not drive any significant expression when coinjected with other constructs and that the Tbr site is a functional in vivo binding site.

We then compared the expression driven by our primary and secondary sites using this reporter system. Tbr levels are very high maternally and throughout early development as shown by western blot (supplementary fig. S3A, Supplementary Material online). Using qRT-PCR, we show that 2° Tbr GFP and OtxG GFP drive expression at roughly the same levels in vivo at three early developmental time points: 21 h (two-tailed t-test, \( t = 0.404, df = 4, P = 0.650 \)), 25 h (two-tailed t-test, \( t = 1.505, df = 6, P = 0.148 \)), and 28 h (two-tailed t-test, \( t = 0.296, df = 12, P = 1 \), Bonferroni corrected) (fig. 4C). These data, therefore, convincingly show that Tbr is able to use the secondary site in place of the naturally occurring primary site in vivo and with no significant change in transcription of the reporter. This suggests that at these time points, there are sufficient levels of Tbr present to overcome the differential affinity for these sites, and therefore, Tbr binds either the primary or secondary site interchangeably to drive gene expression.

We next sought to determine whether the Tbr protein could differentiate between these sites when protein levels are reduced. To this aim, we coinjected each construct with either 400 \( \mu \)M control morpholino antisense oligonucleotide (MASO) or PrnTbr-specific translation blocking MASO. These modified oligonucleotides bind in a sequence specific manner to the translation start site of the transcript to block translation and have been used successfully in previous work from our lab (Hinman et al. 2007; McCauley et al. 2010). At this concentration, the Tbr MASO drastically reduces, but does not eliminate, Tbr protein. Knock-down efficiency of all samples was confirmed by assaying for changes in expression of known Tbr target genes, otxβb and delta, by qRT-PCR (supplementary fig. S3B, Supplementary Material online) (Hinman and Davidson 2007). Therefore, we are confident that our Tbr MASO is reducing levels of Tbr protein. In a Tbr knockdown, 2° Tbr GFP drives expression at 40% the level of its expression in sibling Control MASO embryos at 28 h (two-tailed t-test, \( t = 6.360, df = 4, P = 0.0067, \) Bonferroni corrected) (fig. 4E). To control for any effects that might be associated with the different reporters in this experiment, we show that at 28 h, normalized expression of OtxG GFP is not significantly different between Tbr MASO and sibling Control MASO embryos (two-tailed t-test, \( t = 1.410, df = 4, P = 0.334 \), Bonferroni corrected). Furthermore, when we consider the expression of OtxG GFP compared with 2° Tbr GFP when they are expressed in Tbr MASO embryos (fig. 4E, comparison between red bars), 2° Tbr GFP is expressed at significantly lower levels (two-tailed t-test, \( t = 3.880, df = 4, P = 0.022 \), Bonferroni corrected). This demonstrates that even though the 2° Tbr GFP construct differs from OtxG GFP by only 2 bp, it is significantly more sensitive to Tbr knockdown than is OtxG GFP. This indicates that the secondary binding site is more sensitive to in vivo protein levels, as predicted from the in vitro affinity data.

The Secondary Site Responds Faster to Tbr’s Endogenous Temporal Gradient

We wanted to determine whether the secondary and primary binding sites would respond differently to endogenously changing levels of Tbr. To test how the primary and secondary sites might differ in their response to a temporal decline in Tbr levels, we first determined when Tbr decreases endogenously. Tbr levels are high maternally, which makes it difficult to determine how genes respond to zygotic Tbr levels as the gene’s transcription is initiated (supplementary fig. S3A, Supplementary Material online). However, we see that during the later gastrula stages, between 54 h and 65 h, Tbr goes from being localized broadly throughout the ectoderm
Fig. 5. Secondary Tbr reporter has reduced expression compared with OtxG in the ectoderm when Tbr levels are declining. (A–A”) In all panels, blue indicates DAPI nuclear stain and red indicates Tbr localization. (A) Thirty-one hours blastula stage *Patiria miniata* embryo; (A’) 52-h gastrula stage embryo; and (A”) 65-h late gastrula stage embryo. Arrow heads indicate localization, which is present in only the ciliary band ectoderm by 65 h. (B–E”) 2682 Cheatle Jarvela et al. doi:10.1093/molbev/msu213 MBE

(continued)
(31 h and 52 h embryos) to being specifically localized within the ciliary band territory within the ectoderm (fig. 5A). We also see an overall reduction in Tbr levels between 48 h and 70 h by western blot (supplementary fig. S3A, Supplementary Material online). The otx gene, regulated by Tbr through the OtxG CRM, has a similar progression of its expression domain and time course (Hinman, Nguyen, and Davidson 2003).

We therefore determined whether expression driven by the 2° Tbr GFP reporter extinguishes more rapidly in the ectoderm between 54 h and 65 h than that driven by OtxG. We examined the expression of GFP and mCherry reporters using FISH. In all of these stages, endoderm expression of Tbr is high (Hinman, Nguyen, Cameron, et al. 2003), which necessitates spatial comparison of transcripts localized to the ectoderm as opposed to qRT-PCR, which can only determine global transcriptional levels. We examined the spatial coexpression of GFP and mCherry in appropriately staged embryos and then quantified levels of expression in these cells. As in our qRT-PCR experiments, we normalize the level of GFP expression driven by OtxG GFP and 2° Tbr GFP to mCherry levels driven by OtxG mCherry. We first confirmed that OtxG GFP and OtxG mCherry coexpress in the same cells in early (28 h, fig. 5B–B”) and late development (56 h, fig. 5D–D”), so that mCherry expression can be used for normalization of fluorescent intensity. We next show that 2° Tbr GFP and OtxG mCherry also coexpress in the same set of cells at these time points (fig. 5C–C” and 5E–E”). Finally, we quantify and compare the normalized GFP expression driven by primary and secondary motifs in early development (28 h) when Tbr levels are high and in late development (56 h) when Tbr levels are low.

At 28 h, we show that OtxG GFP does not drive significantly different expression in the ectoderm compared with 2° Tbr GFP (two-tailed t-test, t = 0.663, df = 18, P = 0.987, Bonferroni corrected). Thus, at this stage, as predicted by our earlier quantitative assays, there is no effect of primary versus secondary binding site on the abundance of reporter gene expression, and we also show here on spatial localization. When we compare the expression of 2° Tbr GFP to OtxG GFP at 56 h, however (compare ratio of E/E’ to D/D’; fig. 5E), we find that 2° Tbr GFP reporter is expressed in reduced patches and at visually lower levels. Quantification of fluorescent intensities of normalized GFP signals demonstrates significant reduction of 2° Tbr GFP expression relative to OtxG GFP (two-tailed t-test, t = 6.109, df = 28, P = 0.0000019, Bonferroni corrected). These data (figs. 4 and 5) show that a 2 bp change from the higher affinity primary to the lower affinity secondary Tbr binding site is sufficient to elicit a response to reduced Tbr levels that is more pronounced than the wild-type response.

**Discussion**

There has been a great deal of interest and controversy surrounding theories of how developmental GRNs might evolve. Debate has centered on the effects that protein versus cis-regulatory mutations may have on the capacity for change in a GRN. Much work suggests that CRM variation is the prominent source of change to GRNs and evolution of novel phenotypes (reviewed in Wray 2007; Rebeiz and Williams 2011; Wittkopp and Kalay 2012; Rubinstein and de Souza 2013). There are many explanations for why CRMs are so equipped to evolve, but a crucial source of their evolutionary flexibility is their modularity. A single gene is frequently regulated by many CRMs, each CRM orchestrating expression of that gene in a specific spatiotemporal context (Armone and Davidson 1997). So then, a particular CRM for a given gene can be lost, gained, or altered independently from all of the other CRMs, and likewise, binding sites within a CRM can be lost, gained, or altered independently from the rest of the sites within the CRM. These properties create a scenario with very little pleiotropy and as a result, a great deal of evolutionary freedom.

A key to understanding how protein changes can affect GRNs therefore is to understand the ways that proteins can themselves evolve in ways that reduce pleiotropy. In actuality, proteins are often composed of multiple domains, which may be gained, lost, and changed independently of each other to create diverse proteins (Levitt 2009; Wang and Caetano-Anollés 2009; Kersting et al. 2012). Each domain has the capacity to be modified individually, and some of these modifications may limit the activity of the protein to a specific time and place. A novel protein–protein interaction, for example, might limit the activity of a protein to contexts where it is coexpressed with its new cofactor. It is unsurprising then that changes in protein–protein interactions (Löhr and Pick 2005; Tuch et al. 2008) and post-translational modifications (Lynch et al. 2011) also allow for the evolution of novel features and rewritten of GRNs.

Understanding of how transcription factors might directly evolve changes in DNA-binding properties has been less clear. Outside of a few striking examples (Hanes and Brent 1989; Baker et al. 2011; Nakagawa et al. 2013), it has been considered that this feature of transcription factor function will remain highly conserved and will not represent a substantial source of evolutionary novelty. Recent work, however, demonstrates that DNA-binding properties also have a capacity to be modular as they can have secondary or alternative binding preferences in addition to their primary or most preferred binding site (Badis et al. 2009; Gordan et al. 2011; Busser et al. 2012;

**Fig. 5. Continued**

In all panels, blue indicates DAPI nuclear stain, red indicates mCherry transcripts labeled by CyIII, and green indicates GFP transcripts labeled by fluorescein. (B), (C), (D), and (E) depict the entire embryo with merged expression, whereas (B’–B”), (C’–C”), (D’–D”), and (E’–E”) are insets of the region of interest for each probe. (B’–C”) OtxG GFP and 2° Tbr GFP both coexpress spatially with OtxG mCherry at 28 h (D’–D”). OtxG GFP reporter coinjected with OtxG mCherry at 56 h. The reporters are still spatially coexpressed at this stage. (E’–E”) 2° Tbr GFP reporter coinjected with OtxG mCherry at 56 h. GFP expression is reduced compared with OtxG GFP, whereas mCherry levels remain more consistent. (F) Quantification of fluorescent intensities of fluorescein (GFP) relative to CyIII (mCherry) at 28 h and 56 h. N indicates the number of embryos imaged. Error bars indicate standard error of the mean. P values indicate the result of two-tailed t-tests, which are described in the Results.
This finding points to a previously overlooked source of modularity for evolution to exploit and, therefore, to a mechanism for allowing a transcription factor to evolve a new function. We speculate that PmTbr may be able to carry out multiple developmental functions simultaneously by dividing them among its two binding motifs. PmTbr is needed for the correct specification of endoderm, mesoderm, and ectoderm during sea star embryogenesis (Hinman and Davidson 2007; Hinman et al. 2007; McCauley et al. 2010). Meanwhile, SpTbr has a single role in the sea urchin embryo, which is to specify skeletogenic mesenchyme (Crote et al. 2001; Oliveri et al. 2002). Even within the skeletogenic network, SpTbr has relatively few inputs into skeletogenic genes (Rafiq et al. 2012) suggesting that it is a much less pleiotropic gene than PmTbr. In hemichordates and cephalochordates, the Tbr ortholog is also expressed in multiple embryonic tissue types, including endoderm and ectoderm (Tagawa et al. 2001; Horton and Gibson-Brown 2002), suggesting that these orthologs and PmTbr may share an ancestral function in the endoderm and ectoderm that must have been lost in sea urchins.

The ability to divide functions between different binding motifs has potential to be very useful during development because a limited number of regulatory molecules must orchestrate the specification of an increasingly complex embryo. Ideally, such regulatory molecules will be as multifunctional as possible to allow development to progress rapidly and create diverse cell types. Yet, this pleiotropy is what causes transcription factors to be evolutionarily constrained. Our finding that these functions can be uncoupled and evolve independently through separate binding sites offers a mechanism by which new features can arise.

We also demonstrate that the secondary binding site is more responsive to changes in Tbr protein levels during development. This quality is particularly important for functions that require rapid transcriptional responses and may be especially important during early development when the timing of developmental events must be precisely coordinated. We predict such affinity differences are also advantageous when a rapid transcriptional response is required during development for some but not all target genes (fig. 6). Such targets can make use of more sensitive, lower affinity secondary sites.

It is often assumed that transcription factors are under an enormous amount of evolutionary constraint because they regulate large numbers of target genes. Presumably, these targets are essential to the organism and must be maintained by all orthologs that arise by speciation. However, if these target genes are subdivided into groups based on the binding sites they are regulated by, then there are fewer genes affected by changes in binding preference. This reduces pleiotropy, because a loss of ability to use a secondary site would affect only a subset of target genes, whereas others would be regulated normally (fig. 6). SpTbr should be able to maintain developmental functions associated with the primary site, yet its reduced ability to utilize a secondary site may have led to evolutionary differences in cell patterning and specification between these species. This modification in function between orthologs will not only lead to a dramatic loss or gain of target
genes but also offers a mechanism to affect timing control of gene regulation. Change in relative order or timing of developmental events can be acquired by evolving higher or lower affinity for a secondary binding site. We hypothesize that this newfound source of modularity in orthologous transcription factors offers a previously overlooked source of GRN evolutionary change.

**Materials and Methods**

**Phylogenetics**

Tbr orthology was established using a MrBayes model (JTT plus Gamma), 5 runs, 100,000 generations, sampling frequency of 10, in TOPALi v2.5 (Milne et al. 2004). Branches are supported by posterior probability. The T-box domain alignment of all represented proteins was generated by Clustal Omega (Sievers et al. 2014) and is shown in supplementary figure S1, Supplementary Material online. Accession numbers are listed in supplementary figure S1, Supplementary Material online.

**Protein Expression and Purification of DNA-Binding Domains**

GST fusion protein constructs for protein-binding microarray, and SPR were made by cloning T-box sequences into pKM vector and were purified from BL21 *E. coli*. The T-box domain constructs consisted of residues 272–466 of *Pm*Tbr and residues 362–554 of *Sp*Tbr to include the whole T-box plus five amino acids flanking each side. Cultures were grown at 20°C, and protein expression was induced by addition of 0.2 mM IPTG at OD600 0.5, and growth was continued overnight. Cell pellets were resuspended in PBS Triton x-100 (0.1% v/v) (pH 7.5) for protein-binding microarrays or 20 mM Mops (pH 7.5), 150 mM NaCl, 1 mM DTT, and 0.005% Surfactant P20 (v/v) for SPR. In both cases, complete protease inhibitors (Roche Diagnostics, Indianapolis, IL) were added just prior to use, and cells were lysed by sonication. All fusion proteins were purified by GSH affinity chromatography (Thermo Scientific Pierce, Rockford, IL). For protein-binding microarray experiments, glycerol was added to eluted proteins to 10% (v/v), and single-use aliquots were flash-frozen and stored at −80°C. For SPR protein samples, T-box DNA-binding domains were cleaved from GST-His on beads by treatment with TEV protease (Eton Bioscience, San Diego, CA). DNA-binding domains were then flash frozen and stored at −80°C in single-use aliquots.

**Protein-Binding Microarrays**

Custom-designed, “universal” oligonucleotide arrays (Agilent Technologies, AMADID #016060 [Zhu et al. 2009]) were converted to double-stranded DNA arrays by primer extension and used in protein-binding microarray experiments essentially as described previously (Berger et al. 2006); 200 nM samples of *Pm*Tbr and *Sp*Tbr were assayed in PBS (pH 7.5). Two replicate data sets for each protein are reported in supplementary table S1, Supplementary Material online. Microarrays were scanned and quantified and then analyzed using the Universal PBM Analysis Suite and the Seed-and-Wobble motif derivation algorithm as described previously (Berger et al. 2006; Berger and Bulyk 2009).

**Surface Plasmon Resonance**

The sequences of 5’Biotin-labeled hairpin DNA oligomers are depicted in figure 3A; 25 nM stocks of hairpin oligomers were diluted in HBS-EP buffer (0.01 M HEPES, pH 7.4, 0.15 M NaCl, 3 mM ethylenediaminetetraacetic acid [EDTA], 0.005% Surfactant P20). These were applied to a streptavidin-coated CMS chip, prepared according to Nguyen et al. (2006), with minor modifications for a Biacore T100 SPR instrument. The first flow cell was left blank for reference subtraction, whereas primary, secondary, and nonspecific DNA hairpins were immobilized to flow cells 2–4, respectively, such that each had 150 RUs of DNA. Separate chips were made to assess affinity for *Pm*Tbr secondary and *Mm*Eomes secondary sites (both on flow cell 3 of their respective chips). Both chips were designed with the primary site hairpin on flow cell 2 and nonspecific hairpin on flow cell 4. Because the maximal binding capacity of each chip was not equivalent, this necessitated that the data shown in figure 3C and D be split into separate
graphs. The sensor chip was washed several times in running buffer prior to use (50 mM Mops, 150 mM NaCl, 1 mM DTT, and 0.01% [vol/vol] P20 surfactant). Kinetic measurements were performed at 20 °C with a flow rate of 30 µl/min. Tbr DNA-binding domain protein samples were run alternately across the same chip, and all four flow cells were exposed to a sample simultaneously. The concentration series was scrambled for each protein. Immediately following protein injection, buffer was injected to monitor dissociation. Zero concentration (buffer only) samples were included and used to subtract background from protein samples. Data were analyzed first using the BlaEvaluation software to determine steady-state response levels for each concentration 95 seconds after injection start. These data were then evaluated using Origin and a 1:1 binding model to determine K_d.

Embyro Culture and Injection
Patiria miniata embryos were obtained and injected as described in Hinman, Nguyen, Cameron, et al. (2003) and Cheatle Jarvela and Hinman (2014).

Reporter Expression Constructs
OtxG GFP and Basal promoter GFP reporter constructs were developed by Hinman et al. (2007), 2° Tbr GFP, Tbr Deletion GFP, and OtxG mCherry were developed from these existing constructs using the methods described in Hinman et al. (2007). Primer sequences are provided in supplementary table S2, Supplementary Material online.

Fluorescent Whole-Mount In Situ Hybridization
FISH was performed as previously described (Yankura et al. 2010) using digoxigenin- or dinitrophenol-labeled antisense RNA probes targeted to GFP and mCherry, respectively. Samples consisted of cohorts of sibling embryos injected with either OtxG GFP or OtxG mCherry or 2° Tbr GFP plus OtxG mCherry. Embryos were reared at 15 °C until 28 h or 56 h.

Image Analysis
FISH embryos were imaged with a Carl Zeiss LSM-510 Meta DuoScan Inverted Confocal Microscope. Laser power, gain, and digital offset settings were optimized for embryos injected with OtxG GFP or OtxG mCherry and then left unchanged for subsequent imaging of sibling embryos injected with 2° Tbr GFP plus OtxG mCherry. The relative fluorescence of mCherry transcripts (CyIII) to GFP transcripts (fluorescein) was quantified using ImageJ (National Institutes of Health, Bethesda, MD). All images were background subtracted using “BG subtraction from ROI” plugin prior to analysis. The “Measure” function was used to determine the mean fluorescence value of a region of interest for both channels.

Quantitative RT-PCR
Total RNA from injected embryos was obtained using GenElute Mammalian Total RNA kit (Sigma, St. Louis, MO). The total RNA was used to make cDNA using iSCRIPT Select cDNA synthesis kit (Bio-Rad, Hercules, CA). Quantitative RT-PCR (qRT-PCR) was performed according to Hinman, Nguyen, Davidson (2003) using an Applied Biosystems 7300 Real-Time PCR system along with SYBR green PCR master mix. The threshold cycle number (Ct) was normalized to nuclear pore protein, lamin2β receptor (accession: KJ868807) (supplementary fig. S3B, Supplementary Material online) for endogenous gene expression, or mCherry mRNA for reporter gene expression (fig. 4C–E). Primer sequences are provided in supplementary table S2, Supplementary Material online.

Immunofluorescence
Patiria miniata embryos were fixed in 4% paraformaldehyde/PBS for 20 min at RT, followed by permeabilization in 1% Triton X-100/PBS for 10 min. Embryos were then washed four times in PBS/0.1% Triton X-100 and post-fixed in ice cold methanol for 20 min. After another four washes, embryos were blocked in 3% BSA/PBS for 30 min and incubated with anti-PmTbr (1:500) overnight at 4 °C. Affinity purified polyclonal anti-PmTbr was produced in rabbits by Piece Custom Antibody Services. Embryos were washed four times and incubated in 1:100 FITC anti-rabbit (Sigma) overnight. Embryos were incubated in 1:10,000 DAPI (Life Technologies) for 30 min, washed four times in PBS/0.1% Triton X-100.

Embryos were imaged in Slowfade mounting media (Life Technologies) by confocal microscopy.

Chromatin Immunoprecipitation PCR
ChIP was carried out as described by Mortazavi et al. (2006), with several modifications for sea star embryo samples. Chromatin extraction was performed as follows. Roughly 10⁶ P. miniata embryos (~10⁷ cells) were collected at 30 h postfertilization. These were cross-linked in 1% formaldehyde in artificial sea water for 10 min, stopped with 0.125 M glycine, collected by centrifugation, and washed 3x in cold PBS. Embryos were resuspended in lysis buffer (5 mM 1,4-piperazine-bis-[ethanesulfonic acid] [pH 8.0], 85 mM KCl, 0.5% NP-40, complete protease inhibitors [Roche Diagnostics]). After 10 min of lysis on ice, the embryos were passed through a 25-gauge needle 5–10 times and centrifuged to collect the crude nuclear preparation. Chromatin was digested to 500–100 bp pieces by micrococcal nuclease (New England Biolabs, Ipswich, MA) according to the SimpleChIP Enzymatic Chromatin IP Kit protocol (Cell Signaling Technology, Danvers, MA). The nuclear pellet was collected by centrifugation and lysed on ice for 10 min in 50 mM Tris (pH 8), 10 mM EDTA, 1% SDS (w/vol), and protease inhibitors. After the lysate was clarified by centrifugation, small aliquots were flash-frozen for immunoprecipitation, which was performed as described (Mortazavi et al. 2006).

Enrichment of the PmOtxG regulatory region was examined by PCR. A primer set was designed for an amplicon within the 850 bp CRM. Amplicons corresponding to regions 1 kb upstream and 1 kb downstream of OtxG were used as negative controls. Primer sequences are available in
supplementary table S2, Supplementary Material online. PCR was performed for 30 cycles to achieve a linear range with the following conditions: 94 °C for 30 s, 58 °C for 30 s, and 72 °C for 20 s. All reactions contained 1 ng template (total chromatin, mock ChIP, or Tbr ChIP). Products were analyzed by 1% agarose gel.

Supplementary Material
Supplementary tables S1 and S2 and figures S1–S3 are available at Molecular Biology and Evolution online (http://www.mbe.oxfordjournals.org/).

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