

Phenotypic and transcriptional response to selection for alcohol sensitivity in *Drosophila melanogaster*

Tatiana V Morozova^{*†‡}, Robert RH Anholt^{*†§} and Trudy FC Mackay^{†§}

Addresses: ^{*}Department of Zoology, North Carolina State University, Raleigh, NC 27695, USA. [†]WM Keck Center for Behavioral Biology, North Carolina State University, Raleigh, NC 27695, USA. [‡]Institute of Molecular Genetics RAS, Kurchatov Square, Moscow 123182, Russia. [§]Department of Genetics, North Carolina State University, Raleigh, NC 27695, USA.

Correspondence: Trudy FC Mackay. Email: trudy_mackay@ncsu.edu

Published: 31 October 2007

Genome Biology 2007, **8**:R231 (doi:10.1186/gb-2007-8-10-r231)

The electronic version of this article is the complete one and can be found online at <http://genomebiology.com/2007/8/10/R231>

Received: 1 May 2007

Revised: 31 July 2007

Accepted: 31 October 2007

© 2007 Morozova et al.; licensee BioMed Central Ltd.

This is an open access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/2.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract

Background: Alcoholism is a complex disorder determined by interactions between genetic and environmental risk factors. *Drosophila* represents a powerful model system to dissect the genetic architecture of alcohol sensitivity, as large numbers of flies can readily be reared in defined genetic backgrounds and under controlled environmental conditions. Furthermore, flies exposed to ethanol undergo physiological and behavioral changes that resemble human alcohol intoxication, including loss of postural control, sedation, and development of tolerance.

Results: We performed artificial selection for alcohol sensitivity for 35 generations and created duplicate selection lines that are either highly sensitive or resistant to ethanol exposure along with unselected control lines. We used whole genome expression analysis to identify 1,678 probe sets with different expression levels between the divergent lines, pooled across replicates, at a false discovery rate of $q < 0.001$. We assessed to what extent genes with altered transcriptional regulation might be causally associated with ethanol sensitivity by measuring alcohol sensitivity of 37 co-isogenic *P*-element insertional mutations in 35 candidate genes, and found that 32 of these mutants differed in sensitivity to ethanol exposure from their co-isogenic controls. Furthermore, 23 of these novel genes have human orthologues.

Conclusion: Combining whole genome expression profiling with selection for genetically divergent lines is an effective approach for identifying candidate genes that affect complex traits, such as alcohol sensitivity. Because of evolutionary conservation of function, it is likely that human orthologues of genes affecting alcohol sensitivity in *Drosophila* may contribute to alcohol-associated phenotypes in humans.

Background

Alcohol abuse and alcoholism are significant public health problems throughout the world. In the United States alone, they affect approximately 14 million people at a health care cost of \$184 billion per year [1].

Identifying genes that predispose to alcoholism in human populations has been hampered by genetic heterogeneity and the inability to control environmental factors, and the reliance on complex psychiatric assessments and questionnaires to quantify alcohol-related phenotypes. Despite these

disadvantages, studies in ethnically defined populations have implicated alleles of alcohol dehydrogenase, aldehyde dehydrogenase, the GABA_A receptor complex, and the serotonin 1B receptor as contributing to variation in alcohol sensitivity (reviewed in [2-5]). Recently, large scale gene expression profiling identified candidate alcohol responsive genes in human brains [6-10], including genes that encode proteins involved in myelination, neurodegeneration, protein trafficking as well as calcium, cAMP, and thyroid signaling pathways. It is, however, difficult to design large scale experiments in humans to verify causal roles for these candidate genes.

Studies in mice have provided further support for important roles of serotonin, GABA_A and dopamine receptors as well as opioid peptides (reviewed in [11,12]) in modulating the effects of alcohol. In addition, four classes of protein kinases, PKA, PKC, PKG and Fyn kinase, have been identified as critical mediators of the effects of alcohol [13-16]. Changes in brain gene expression following exposure to alcohol have also been observed in inbred mouse strains for multiple genes associated with the Janus kinase/signal transducers and activators of transcription, the mitogen activated protein kinase pathways, and retinoic acid mediated signaling [17].

With its well annotated genome and amenability to powerful genetic manipulations, *Drosophila* presents an attractive model organism for studies on the genetic architecture of alcohol sensitivity [18,19]. Although flies do not exhibit addictive behavior according to the formal criteria for diagnosing substance abuse disorders in humans [5], alcohol sensitivity and the development of alcohol tolerance in flies show remarkable similarities to alcohol intoxication in vertebrates, suggesting that at least some aspects of the response to alcohol may be conserved across species [20]. Moreover, two-thirds of human disease genes have orthologues in *Drosophila* [21]. Exposing flies to low concentrations of ethanol stimulates locomotor activity, whereas high concentrations of ethanol induce an intoxicated phenotype, characterized by locomotor impairments, loss of postural control, sedation and immobility [22,23].

Studies to date have used mutant screens and expression profiling of flies after exposure to alcohol and after development of tolerance to identify genes associated with ethanol sensitivity in *Drosophila* [19,24-29]. An alternative strategy to discover genes affecting complex behaviors is to combine artificial selection for divergent phenotypes with whole genome expression profiling [3,30-33]. The rationale of this approach is that genes exhibiting consistent changes in

expression as a correlated response to selection are candidate genes affecting the selected trait [33].

Here, we performed 35 generations of artificial selection from a genetically heterogeneous base population to derive replicate lines that are sensitive or resistant to ethanol exposure, as well as unselected control lines. We used whole genome transcriptional profiling to identify genes that are differentially expressed between the selection lines. Functional tests of mutations in 35 of the differentially expressed genes confirmed 32 novel candidate genes affecting alcohol sensitivity, including three (*Malic enzyme*, *nuclear fallout* and *longitudinals lacking*) that have been previously associated with alcohol sensitivity and/or tolerance in *Drosophila* [19]. A high proportion of this subset of candidate genes (72%) has human orthologues and their human counterparts are, therefore, relevant candidate genes that may predispose to alcohol sensitivity and alcohol abuse in human populations.

Results

Phenotypic response to artificial selection for alcohol sensitivity

We constructed a heterogeneous base population from isofemale lines sampled from a Raleigh natural population and used artificial selection to create replicate genetically divergent lines with increased resistance (R) or sensitivity (S) to ethanol exposure. We also generated replicate unselected control (C) lines to enable us to monitor the symmetry of the response and genetic drift. Lines had established maximum divergence after 25 generations of selection. At generation 25, the mean elution time (MET) for the replicate control lines (C1 and C2) was MET = 7.4 minutes and MET = 8.8 minutes, respectively; for the replicate sensitive lines (S1 and S2), MET = 2.9 minutes and MET = 2.7 minutes, respectively; and for the replicate resistant lines (R1 and R2), MET = 17.6 minutes and MET = 19.3 minutes, respectively (Figure 1a). Thus, the R and S replicate lines diverged from each other by an average of 15.65 minutes at generation 25. The response to selection was symmetrical. Realized heritability estimates from the divergence between R and S lines over 25 generations were $h^2 = 0.081 \pm 0.0097$ ($P < 0.0001$) and $h^2 = 0.069 \pm 0.0096$ ($P < 0.0001$) for the respective replicates (Figure 1b). After generation 25 there was almost no response to selection. Realized heritability estimates from the divergence between R and S lines from generation 25 to 35 were $h^2 = -0.056 \pm 0.036$ ($P = 0.1567$) and $h^2 = 0.0031 \pm 0.027$ ($P = 0.91$) for the respective replicates.

Figure 1 (see following page)

Phenotypic response to selection for alcohol sensitivity. **(a)** MET for selection lines. Resistant lines are shown as orange squares, control lines as grey triangles, and sensitive lines as blue circles. Solid lines and shapes represent replicate 1; dashed lines and open shapes denote replicate 2. **(b)** Regressions of cumulative response on cumulative selection differential for divergence between resistant and sensitive selection lines. The blue line and squares represent replicate 1; the orange line and circles denote replicate 2.

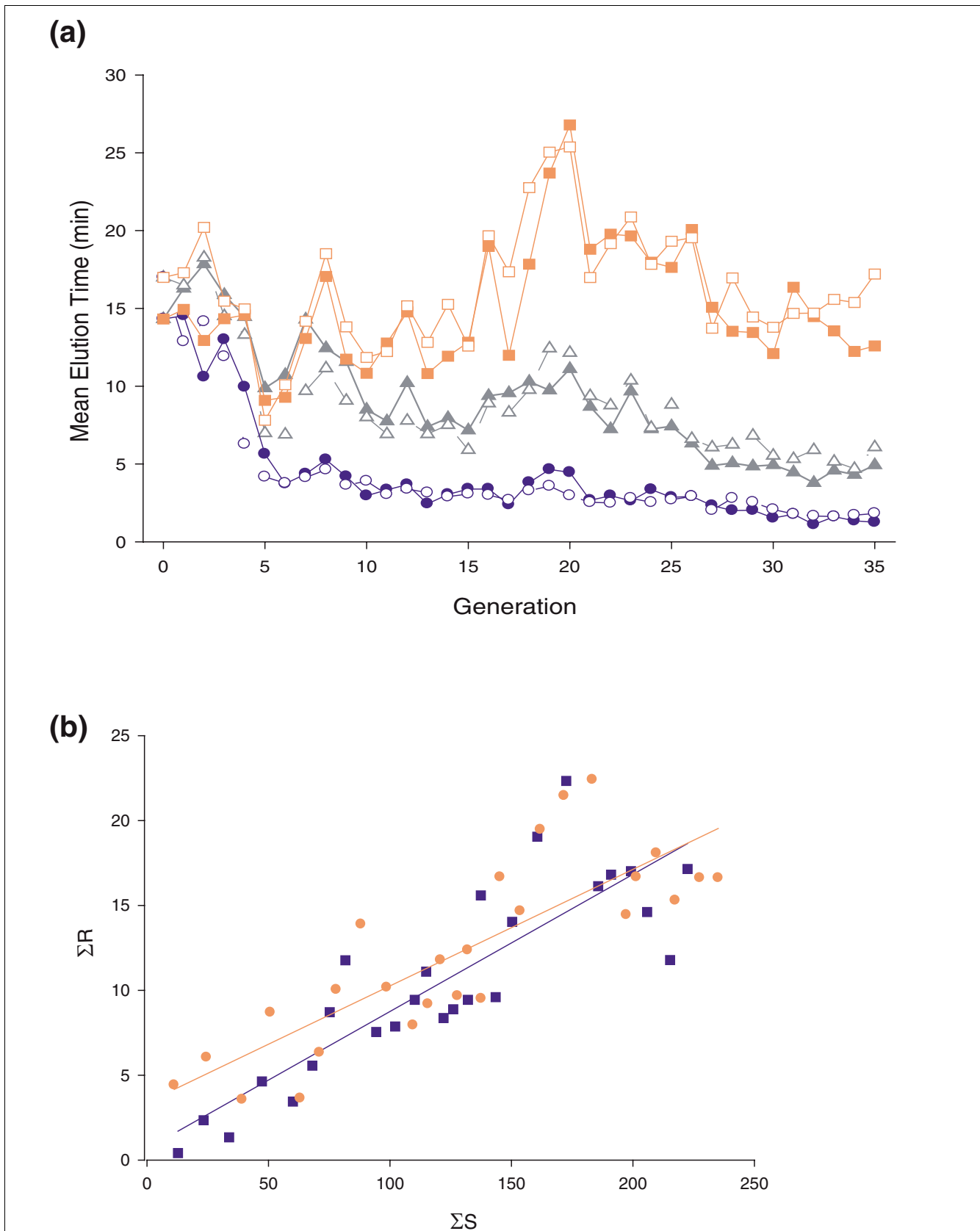


Figure 1 (see legend on previous page)

Correlated phenotypic responses to selection for alcohol sensitivity

Exposure to alcohol affects locomotion [22,23]. Furthermore, in human populations excessive alcohol consumption can give rise to aggressive and violent behaviors [34-36]. Alcohol sensitivity also depends on metabolic and physiological state [37-41]. In addition, exposure to alcohol results in an acute down-regulation of the expression of a group of odorant receptors and odorant binding proteins [19], which raises the question whether artificial selection for alcohol sensitivity would be associated with a reduction in olfactory ability. To assess whether the response to selection was specific for alcohol sensitivity or whether other phenotypes underwent correlated selection, we tested the selection lines for locomotion, aggression, starvation resistance, and olfactory behavior.

We found no differences in locomotor behavior among the selection lines using either an assay for locomotor reactivity ($F_{2,3} = 3.14$, $p = 0.18$; Figure 2a) or a climbing assay ($F_{2,3} = 1.48$, $p = 0.36$; Figure 2b). The selection lines also did not differ in the number of aggressive encounters under conditions of competition for limited food ($F_{2,3} = 3.10$, $p = 0.19$; Figure 2c). Selection lines also did not differ in starvation resistance ($F_{2,3} = 0.56$, $p = 0.64$; Figure 2d). Finally, there was no correlation between alcohol sensitivity and olfactory avoidance behavior over a range of concentrations of the repellent odorant benzaldehyde ($F_{2,3} = 0.40$, $p = 0.70$; Figure 2e) (although there were significant differences between replicates of selection lines in avoidance response ($F_{3,3} = 455.36$, $p = 0.0002$), with line S2 showing reduced olfactory responsiveness). Our results, therefore, indicate that the response to selection was specific for alcohol sensitivity.

Alcohol dehydrogenase gene frequencies

Drosophila encounters ethanol in its natural habitat, as flies feed on fermented food sources. Natural selection, at least under some environmental conditions, affects allele frequencies of the *Alcohol dehydrogenase* (*Adh*) locus, which is polymorphic for two allozymes, which differ by a single amino acid (T192K), designated Slow and Fast, based on their gel migration profile [42,43]. Fast homozygotes have a higher level of enzymatic activity than Slow homozygotes and a higher tolerance to alcohol in laboratory toxicity tests [44-46].

To assess whether differences in alcohol sensitivity in our selection lines could be attributed in part to the Slow and Fast electrophoretic alleles of *Adh* [45,47], we developed a single nucleotide polymorphism marker for this polymorphism and measured allele frequencies in our selection lines. Frequencies of the Fast allele in the replicate control lines were 0.79 and 0.24. The R1 and R2 replicate lines had Fast allele frequencies of 0.42 and 0.58, respectively. However, in both the sensitive selection lines the Slow allele was fixed. Previous

studies have shown that flies homozygous for the Slow *Adh* allele are more sensitive to alcohol [46].

Transcriptional response to selection for alcohol sensitivity

We used Affymetrix high density oligonucleotide microarrays to assess whole genome transcript abundance in three- to five-day-old flies of the selection lines at generation 25. Raw expression data have been deposited in NCBI's Gene Expression Omnibus [48] and are accessible through GEO series number (GSE 7614).

We used a stepwise procedure to analyze the data. First, we used factorial ANOVA to quantify statistically significant differences in transcript levels for each probe set on the array. Using a stringent false discovery rate [49] of $q < 0.001$, we found that 9,931 probe sets were significant for the main effect of sex, 2,612 were significant for the main effect of line, and 184 were significant for the line \times sex interaction term (Additional data file 1). Only two genes that were significant for the interaction term were not significant for the main effect of line: *CG1751*, which is involved in proteolysis, and *CG12128*, which encodes a transcript of unknown function.

Next, we used ANOVA contrast statements on the 2,612 probe sets with differences in transcript abundance between selection lines to detect probe sets that were consistently up- or down-regulated in replicate lines [31]. We identified 2,458 probe sets (13% of the total probe sets on the microarray) that differed between the selection lines when pooled across replicates (Additional data file 2).

Among these 2,458 probe sets, 1,572 were divergent between resistant and control lines, 1,617 between sensitive and control lines, and 1,678 between resistant and sensitive selection lines. Although the transcriptional response to selection for alcohol sensitivity was widespread, the magnitudes of the changes in transcript abundance were relatively small, with the vast majority of probe sets showing less than two-fold changes in abundance (Figure 3). In fact, only 121 probe sets showed larger than two-fold differences in transcript abundance. Among these probe sets 37 have not been annotated; 14 encode genes involved in defense response and response to stress, including *Defensin*, *Attacin-A*, *Lysozyme P*, *Immune induced molecules 1, 10, and 23*, and *Metchnikowin*; and 12 probe sets that encode gene products involved in carbohydrate metabolism (*sugar transporter 1*, *Mitogen-activated protein kinase phosphatase 3*, *CG9463*, *CG14959*, *CG10725*, *CG10924*, *Lysozyme P*) (Additional data files 3 and 4).

Categories of genes with differential transcript abundance among sensitive and resistant lines

Probe sets with altered transcript abundance between selection lines fell into all major biological process and molecular function Gene Ontology (GO) categories (Additional data files 5 and 6). We used χ^2 tests to determine which categories were

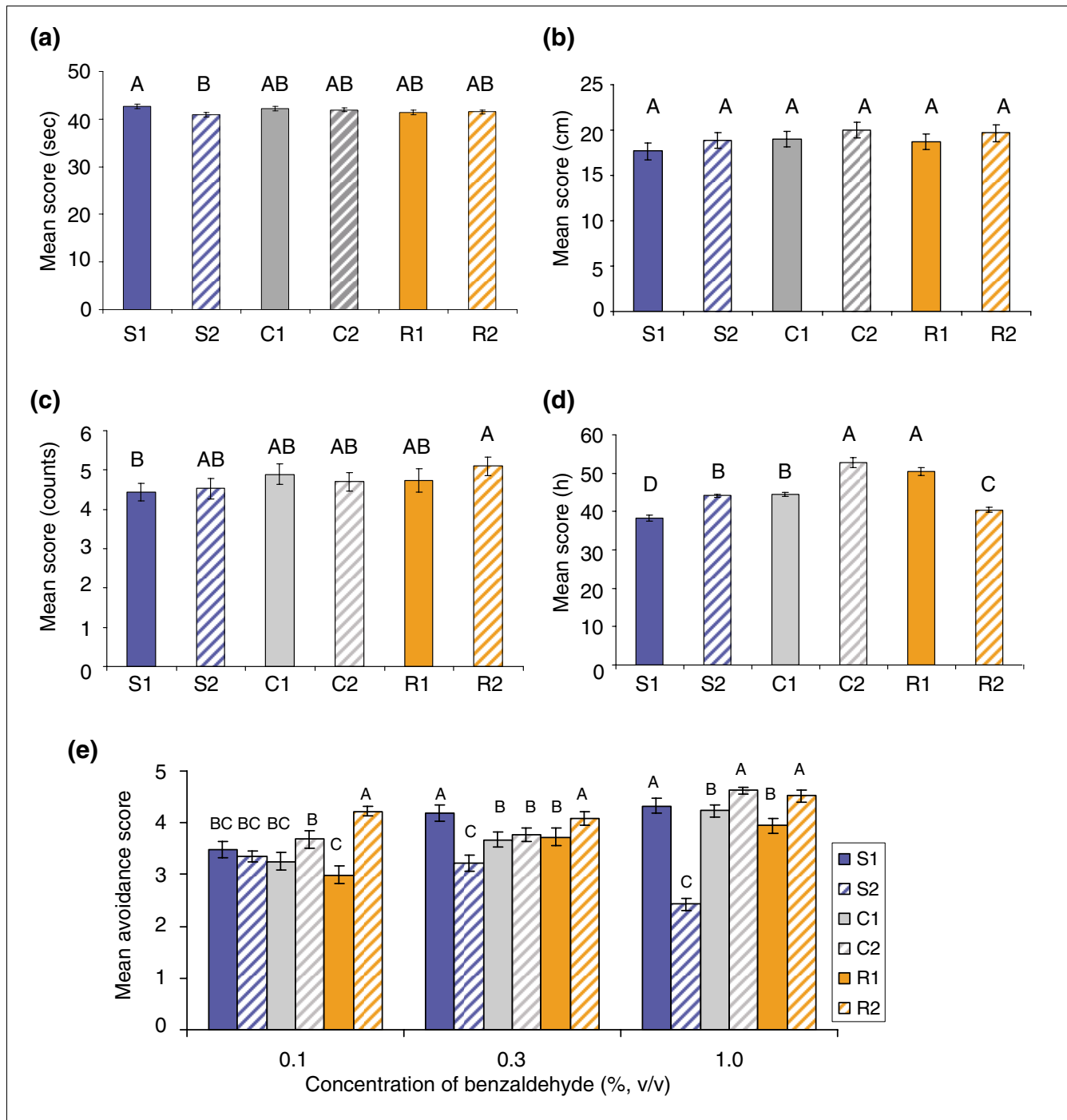


Figure 2 Correlated phenotypic responses to selection. Lines with the same letter are not significantly different from one another at $p < 0.05$. Resistant lines are colored orange, control lines grey, and sensitive lines blue. Solid lines and bars represent replicate 1; dashed bars and lines denote replicate 2. **(a)** Locomotor reactivity; **(b)** climbing behavior; **(c)** aggression behavior; **(d)** starvation resistance; **(e)** olfactory avoidance behavior. Error bars indicate standard errors.

represented more or less frequently than expected by chance, based on their representation on the microarray. One interpretation of these analyses is that over-represented GO categories contain probe sets for which transcript abundance has responded to artificial selection, whereas under-repre-

sented GO categories contain probe sets for which transcript abundance is under stabilizing natural selection [31]. Highlights of the transcriptional response to artificial selection for alcohol sensitivity for probe sets differentially expressed between resistant and sensitive selection lines are given in

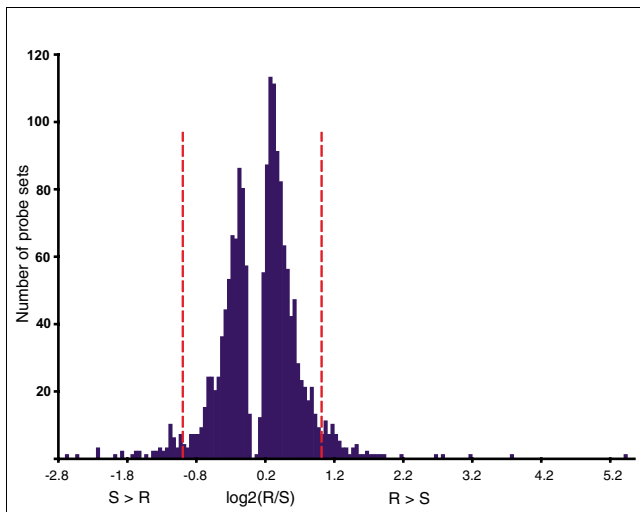


Figure 3
Histogram showing the frequency of relative fold-change in probe sets with significant differences in transcript abundance between resistant (R) and sensitive (S) selection lines, pooled over sexes. The vertical dashed red lines demarcate two-fold changes in transcript abundance.

Table 1. For example, the resistant lines are enriched for up-regulated genes affecting responses to chemical stimulus (including response to toxin and pheromone), extracellular transport, and lipid metabolism; while the sensitive lines are enriched for up-regulated genes affecting alcohol metabolism, defense response, electron transport, catabolism, and lipid and carbohydrate metabolism. Transcripts in the 'response to toxin' GO category are over-represented in both sensitive and resistant lines, but the magnitude of over-representation is higher for resistant lines ($p = 4.19E-7$, compared to $p = 0.029$ for sensitive lines). GO categories for lipid metabolism are notably over-represented in sensitive lines ($p = 1.29E-11$, compared to $p = 1.2E-04$ for resistant lines).

These GO categories correlate well with GO categories that were over-represented during the acute response to a single exposure to ethanol [19], which also resulted in extensive changes in transcript abundance for chemosensory behavior, response to chemical stimulus, and response to toxin.

Pleiotropy

Changes in expression of transcripts during artificial selection for locomotor reactivity, aggression, and alcohol sensitivity [32,33] each encompass a significant percentage of the genome, implying extensive pleiotropy. We found that the transcriptional response to selection for alcohol sensitivity results in changes in expression of over 2,600 probe sets (approximately 14% of the genome) between the selection lines at a stringent false discovery rate of $q < 0.001$. Similarly, transcript abundance of over 1,800 probe sets evolved as a correlated response to selection for increased and decreased levels of locomotor reactivity [33] and expression of over 1,500 probe sets changed during selection for high and low

levels of aggressive behavior [32]. Since these studies used the same initial base population, we could assess overlap in transcripts with altered expression between our selection lines and data from previous studies with lines selected for locomotor reactivity and aggression.

We used χ^2 tests to assess whether we observed more common differentially regulated probe sets than expected by chance. We found 727 probe sets in common between lines selected for alcohol sensitivity and locomotor reactivity ($\chi_1^2 = 883$, $p < 0.0001$); 474 probe sets in common between lines selected for aggressive behavior and locomotor reactivity ($\chi_1^2 = 731$, $p < 0.0001$); and 674 probe sets in common between lines selected for alcohol sensitivity and aggressive behavior ($\chi_1^2 = 986.1$, $p < 0.0001$). The transcript abundance of 307 genes was altered as a correlated response to selection for all three behaviors ($\chi_1^2 = 3928.87$, $p < 0.0001$).

GO categories that were significantly over-represented among these 307 genes include lipid metabolism ($p = 2.2E-16$), electron transport ($p = 1.2E-7$), response to chemical stimulus ($p = 6.1E-5$), carbohydrate metabolism ($p = 9.4E-5$) and generation of precursor metabolites and energy ($p = 8.4E-7$). These genes included 17 members of the cytochrome P450 family and additional genes involved in defense response and/or response to toxin (*Glutathione S transferases D9, E1 and E5; Immune induced molecule 10, Cbl, UDP-glycosyltransferase 35b, Juvenile hormone epoxide hydrolase 1 and 2, Lysozyme P and Peroxiredoxin 2540*; Additional data files 7 and 8). Members of this group of 307 genes appear to represent a common group of environmental response genes.

Functional tests of candidate genes

To validate our premise that transcriptional profiling of artificial selection lines can identify candidate genes that contribute to the trait that responds to selection, we measured alcohol sensitivity of 45 independent *P[GT1]*-element insertion lines corresponding to 35 candidate genes [50,51]. These candidate genes are involved in diverse biological processes, including carbohydrate metabolism (*Malic enzyme, Poly(ADP-ribose)glycohydrolase, CG9674*), regulation of transcription (*little imaginal discs, pipsqueak, lilliputian, longitudinal lacking, CG9650*), nervous system development (*Beadex, Laminin A, longitudinal lacking, muscle-blind, smell impaired 35A*), lipid metabolism (*retinal degeneration B, sugarless, CG17646*) and signal transduction (*β v integrin, Laminin A, sugarless, wing blister, CG32560*). Five of the candidate genes encode predicted transcripts of unknown function (*lamina ancestor, CG11133, CG30015, CG14591 and CG6175*). Overall, 33 (73%) of the *P[GT1]*-element insertion lines exhibited significant differences in alcohol sensitivity compared to co-isogenic *Canton S* (B) control at $p < 0.05$, and for 19 of these lines (58%) statistically significant differences from the control survived Bonferroni correction for multiple tests (Table 2, Figure 4). Remarkably, *P-*

Table 1**Differentially over-represented biological function GO categories between resistant (R) and sensitive (S) lines**

R > S	S > R
Response to abiotic stimulus 1.80E-06*	Alcohol metabolism 4.00E-03
Response to chemical stimulus 1.26E-06	Response to toxin 2.90E-02
Response to toxin 4.19E-07	Response to biotic stimulus 4.32E-05
Response to pheromone 2.10E-08	Defense response 2.13E-05
Chemosensory behavior 8.00E-04	Immune response 1.00E-04
Extracellular transport 2.07E-08	Electron transport 2.88E-05
Lipid metabolism 8.0E-05	Lipid metabolism 2.99E-09
Cellular lipid metabolism 1.20E-04	Cellular lipid metabolism 1.29E-11
Phospholipid metabolism 2.30E-03	Organic acid metabolism 2.37E-07
Steroid metabolism 2.00E-05	Steroid metabolism 9.80E-4
	Fatty acid metabolism 1.56E-10
	Catabolism 1.53E-05
	Cellular catabolism 1.08E-06
	Carbohydrate metabolism 5.20E-05

*p values were calculated from χ^2 tests, estimating which categories were represented more frequently than expected by chance, based on their representation on the microarray.

element insertions implicate 32 out of 35 genes in alcohol sensitivity. *P*-element mutants in *Beadex*, *corto*, *Glutamate oxaloacetate transaminase 1*, *Kinesin-73*, *Laminin A*, *lethal (1) G0007*, *little imaginal discs*, *longitudinals lacking*, *Poly(ADP-ribose) glycohydrolase*, *Malic enzyme*, *muscle-blind*, *nuclear fallout*, *retinal degeneration B*, *sugarless*, *vis-gun*, *wing blister*, *CG6175*, *CG14591*, *CG7832*, *CG17646*, *CG5946* and *CG30015* were more resistant to ethanol exposure than the control. In contrast, mutants for βv *integrin*, *lamina ancestor*, *Lipid storage droplet-2*, *pipsqueak*, *Toll*, *CG9650*, *CG32560*, *CG12505* and *CG9674* were more sensitive to ethanol exposure than the control. Three of these *P*-element insertion lines with transposon insertions at *Malic enzyme*, *nuclear fallout* and *longitudinals lacking* were previously implicated in alcohol sensitivity and/or tolerance in *Drosophila* [19].

Our results demonstrate that transcriptional profiling of artificial selection lines is a powerful strategy for identifying genes that contribute to the selected trait, in our case sensitivity to alcohol.

Discussion

We have used expression microarray analysis to identify genome-wide differences in transcript levels in lines artificially selected for increased resistance or sensitivity to the inebriating effects of ethanol. The realized heritability calculated over 25 generations of selection was modest (approximately 8%). Such heritability is relatively low compared with heritability of locomotor reactivity (approximately 15% [33]) and aggressive behavior (approximately 1% [32]), but it is comparable to realized heritability for mating speed (approximately 7% [31]). There was no correlated phenotypic

response for locomotion, aggression, starvation resistance or olfactory behavior, indicating that the response to selection was confined to alcohol sensitivity. This observation agrees with previous reports, in which no significant differences in alcohol sensitivity were observed between lines artificially selected for low and high levels of aggression [32] or for high and low locomotor activity levels [33] from the same base population used in this study.

Adh alleles

We observed differences in Fast and Slow *Adh* allele frequencies between sensitive and resistant lines. However, the probe set for the *Adh* gene was not differentially expressed between the selection lines. This is perhaps not surprising, as previous studies showed that there is no correlation between ethanol tolerance and ADH activity in lines homozygous for the Fast and Slow *Adh* alleles [52] and the increase in tolerance to ethanol in adult flies was not accompanied by an increase in overall ADH activity [42,53,54].

Whole genome transcriptional profiles of selection lines

Transcriptional profiling studies showed that a large fraction of the genome undergoes altered transcriptional regulation in response to artificial selection, in line with previous selection studies on locomotion, aggression and starvation resistance [32,33,55]. The magnitudes of changes in transcript abundance, although significant at $q < 0.001$, were generally modest. Small (1.3- to 1.4-fold) changes in transcript abundance in response to ethanol exposure have also been reported for other animal models [17]. Similarly, changes in gene expression of as little as 1.4-fold have been detected reproducibly by expression microarray analysis in the brains of human alcoholics [6].

Table 2**Functional tests of candidate genes**

Line	Gene name	MET (SE)	p value	Human orthologue	Biological function
Canton S B	Control	5.4 (0.01)	NA	NA	NA
BG02818	<i>pipsqueak (psq)</i>	3.5 (0.08)	<0.0001	NA	Regulation of transcription, DNA-dependent
BG02327		5.75 (0.22)	0.1776		
BG02845	<i>Toll (Tl)</i>	3.6 (0.09)	<0.0001	<i>toll-like receptor 4*</i>	Defense response, immune response, Toll signaling pathway
BG02317	<i>CG9650</i>	3.6 (0.10)	<0.0001	<i>B-cell lymphoma/leukemia 1 1A*</i>	Regulation of transcription from RNA polymerase II promoter, nucleic acid binding
BG01705		4.9 (0.18)	0.1118		
BG02624		5.6 (0.16)	0.6381		
BG02522	<i>CG32560</i>	3.8 (0.15)	<0.0032	<i>DAB2 interacting protein*</i>	Ras protein signal transduction, G-protein coupled receptor, MAPKKK cascade
BG01371	<i>CG12505</i>	4.3 (0.13)	0.0012	NA	Nucleic acid binding
BG02560	<i>CG9674</i>	4.3 (0.14)	0.0042	NA	Carbohydrate metabolism, amino acid biosynthesis
BG02210	<i>lamina ancestor (lama)</i>	4.6 (0.10)	0.0014	NP_775813, novel gene	Unknown
BG02523		5.7 (0.36)	0.6441		
BG01037	<i>β^v integrin (βInt-v)</i>	4.6 (0.13)	0.0014	NA	Signal transduction, defense response
BG02812	<i>Lipid storage droplet-2 (Lsd-2)</i>	4.7 (0.12)	0.0083	<i>Adipose differentiation-related protein</i>	Lipid transport, sequestering of lipid
BG02830		5.52 (0.23)	0.7909		
BG02518	<i>CG8920</i>	4.7 (0.11)	0.0025	<i>Tudor domain containing protein 7</i>	Nucleic acid binding
BG00987	<i>smell impaired 35A (smi35A)</i>	5.4 (0.14)	0.9859	<i>dual-specificity tyrosine-(Y)-phosphorylation regulated kinase 4</i>	Olfactory behavior, response to chemical stimulus, nervous system development
BG01008	<i>CG11133</i>	5.6 (0.09)	0.6816	NA	Unknown
BG02207	<i>lilliputian (lilli)</i>	5.8 (0.11)	0.0905	<i>Fragile X mental retardation 2 protein*</i>	Regulation of transcription, DNA-dependent
BG2034		6.0 (0.28)	0.1549		
BG02114	<i>CG30015</i>	6.2 (0.17)	0.0120	NA	Unknown
BG01509		5.6 (0.31)	0.4924		
BG02055	<i>little imaginal discs (lid)</i>	6.4 (0.11)	0.0283	<i>Jumonji, AT rich interactive domain 1A</i>	Regulation of transcription, DNA dependent
BG01081	<i>Glutamate oxaloacetate transaminase 1 (Got1)</i>	6.5 (0.10)	0.0048	<i>Glutamic-oxaloacetic transaminase 1</i>	Amino acid metabolism, biosynthesis
BG01013	<i>Poly(ADP-ribose) glycohydrolase (Parg)</i>	6.5 (0.28)	0.0137	<i>Poly(ADP-ribose) glycohydrolase*</i>	Carbohydrate metabolism, glycolysis
BG01389	<i>Laminin A (LanA)</i>	6.8 (0.15)	0.0020	<i>laminin, alpha-5</i>	Proteolysis, signal transduction, central nervous system development
BG02420	<i>CG5946</i>	6.9 (0.15)	<0.0001	<i>Cytochrome b5 reductase 3*</i>	Fatty acid desaturation, cholesterol metabolism
BG01144	<i>CG17646</i>	7.0 (0.16)	0.0002	NA	Lipid metabolism, nucleotide binding
BG02731	<i>longitudinals lacking (lola)</i>	7.1 (0.11)	<0.0001	<i>Zinc finger and BTB domain containing protein 3</i>	Regulation of transcription from RNA polymerase II promoter, nervous system development
BG02501		5.8 (0.31)	0.5457		
BG02276	<i>CG7832</i>	7.6 (0.13)	<0.0001	NA	Protein binding
BG02365	<i>Malic enzyme (Men)</i>	7.7 (0.24)	<0.0001	<i>Malic enzyme 1, NADP(+)-dependent</i>	Malate metabolism, carbohydrate metabolism
BG02180	<i>nuclear fallout (nuf)</i>	8.1 (0.18)	<0.0001	<i>RAB11 family interacting protein 4</i>	Protein binding, actin cytoskeleton reorganization
BG01342	<i>Kinesin-73 (Khc-73)</i>	8.1 (0.21)	<0.0001	<i>kinesin family member 13A</i>	Protein targeting, exocytosis

Table 2 (Continued)

Functional tests of candidate genes

BG02405	<i>corto</i>	8.2 (0.21)	0.0086	NA	Cell cycle, RNA polymerase II transcription factor activity, protein binding
BG00525		5.2 (0.21)	0.2390		
BG02128	<i>lethal (1) G0007 (l(1)G0007)</i>	8.3 (0.13)	<0.0001	<i>DEAH-box protein 38</i>	Nuclear mRNA splicing, via spliceosome; nucleic acid binding
BG01672	<i>CG14591</i>	8.7 (0.20)	<0.0001	<i>Transmembrane protein 164</i>	Unknown
BG01989	<i>visgun (vsg)</i>	8.8 (0.19)	<0.0001	<i>Transmembrane protein 123*</i>	Learning and/or memory, olfactory learning
BG00291	<i>retinal degeneration B (rdgB)</i>	8.9 (0.19)	<0.0001	<i>phosphatidylinositol transfer protein, membrane-associated 2</i>	Lipid metabolism, sensory perception of smell, calcium ion transport
BG01536	<i>Beadex (Bx)</i>	8.9 (0.19)	<0.0001	<i>LIM-only protein 1*</i>	Nervous system development, regulation of transcription from RNA polymerase II promoter
BG01733	<i>CG6175</i>	9.0 (0.20)	<0.0001	NA	Unknown
BG01214	<i>sugarless (sgl)</i>	9.2 (0.20)	<0.0001	<i>UDP-glucose dehydrogenase</i>	Lipid metabolism, cell surface receptor linked signal transduction
BG02679	<i>wing blister (wb)</i>	9.2 (0.15)	<0.0001	<i>laminin, alpha 2*</i>	Signal transduction
BG00990		7.2 (0.13)	0.0093		
BG01127	<i>muscleblind (mb1)</i>	9.6 (0.17)	<0.0001	<i>muscleblind-like 1, isoform b*</i>	Peripheral nervous system development, response to stimulus, nucleic acid binding

Lines that survived Bonferroni significance threshold = 0.0011 are indicated in bold font. Human orthologues have homology scores of >0.98 and bootstrap scores of >83% [86]. *Human orthologues associated with known diseases. NA, not applicable.

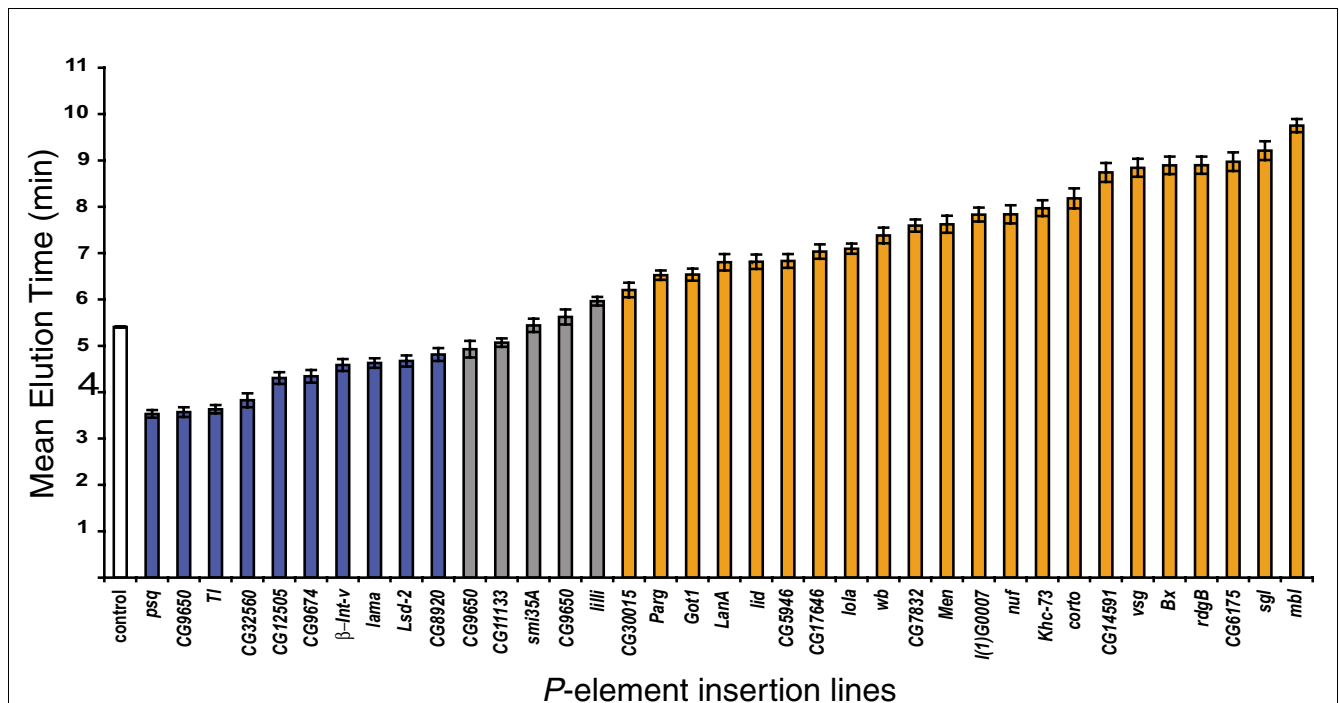


Figure 4

MET of lines containing P-element insertions in candidate genes. The white bar denotes the *Canton S B* co-isogenic control line; grey bars indicate lines with MET not significantly different from the control; blue bars indicate lines significantly sensitive to alcohol vapor to compare with the control ($p < 0.05$); and orange bars indicate lines significantly resistant than the control ($p < 0.05$). Error bars indicate standard errors.

Previously, we observed changes in transcript levels for 582 probe sets after isogenic *Canton S B* flies were exposed to ethanol in an inebriometer [19]. The expression of 195 of these probe sets was also altered between our artificial selection lines ($\chi_1^2 = 152.1$, $p < 0.0001$), including *Adh transcription factor 1*, *Adenylyl cyclase 35C*, 6 cytochrome *P450* family members, *Glutathione S transferases D5, E4, E5 and E7*, *Heat-shock-protein-70*, *Malic enzyme*, *Neural Lazarillo*, *Pheromone-binding protein-related protein 1, 2 and 5*, *Phosphoenolpyruvate carboxykinase*, *Pyruvate dehydrogenase kinase*, and *UDP-glycosyltransferase 35b* (Additional data file 9). One likely reason that we did not detect more of the 582 probe sets previously identified is the difference in genetic background between the two studies (isogenic *Canton S B* versus lines derived from a genetically heterogeneous natural base population).

Verification of candidate genes

Regardless of whether or not the observed changes in gene expression are causally associated with genetic divergence in alcohol sensitivity between the selection lines, the genes exhibiting altered expression levels are candidate genes affecting alcohol sensitivity. We measured the response to ethanol exposure for 45 mutations in candidate genes that were generated in a common co-isogenic *Canton S B* background, and identified 32 genes with mutational effects on alcohol sensitivity. Three of these genes, *Malic enzyme*, *nuclear fallout* and *longitudinals lacking*, have been previously implicated in alcohol sensitivity and/or tolerance [19] and 23 of them have human orthologues, many of which have been implicated in diseases (Table 2).

The high success rate (73%) of these functional tests supports the hypothesis that expression profiling of genetically divergent lines can identify candidate genes that affect complex traits in *Drosophila* and that comparative genomic approaches can infer human candidate genes from their *Drosophila* orthologues. However, we could not detect genes that are differentially expressed at different developmental times. Similarly, genes affecting the trait that are not regulated at the level of transcription, but may be regulated through post-translational modifications, will also not be detected by our transcriptional profiling approach.

We determined how many genes that have been already implicated in alcohol sensitivity and/or tolerance in *Drosophila* are significantly differentially expressed between selection lines, and found 38 genes previously implicated in responses to alcohol or alcohol-related metabolism (Additional data file 10). The probe set for *Aldehyde oxidase 1* [56,57] was not present on the array. Probe sets for the *cheap-date* allele of *amnesiac* [26], the *dopamine D1 receptor* [58] and *neuropeptide F* [59] had absent calls, possibly due to low expression levels, and were consequently not included in the analysis. Of the 34 remaining genes, 10 (approximately 30%) showed altered transcript abundance between our selection

lines at $q < 0.001$, including: *Adh* transcriptional factor 1 [60]; *Acetaldehyde dehydrogenase* [61]; *Aldolase* [62]; *fasciclin II*, which is required for the formation of odor memories and for normal sensitivity to alcohol in flies [25]; *Formaldehyde dehydrogenase* [56,57,63]; *geko* [64]; *Glycerol 3 phosphate dehydrogenase* [56,62,63]; and the cell adhesion receptor *slowpoke*, which encodes a large-conductance calcium-activated potassium channel [65,66].

For 14 previously implicated genes (approximately 40%) the magnitude of the differences in expression after selection for alcohol sensitivity and resistance were not great enough to satisfy our stringent false discovery rate threshold of $q < 0.001$ even if the p value was < 0.05 . Such genes include *dunce* ($q = 0.07$, $p = 0.03$), which encodes a cAMP-phosphodiesterase [26,67]; GABA receptors (*Rdl* and *Lcch3*[68,69]); *lush* ($q = 0.0031$, $p = 0.009$), which encodes an odorant binding protein that interacts with short chain alcohols [70]; the gene that encodes the neuropeptide F receptor ($q = 0.018$, $p = 0.005$) [59]; *period* ($q = 0.007$, $p = 0.03$), a regulator of circadian activity that has been associated with alcohol consumption in mice and humans [28]; *Pka-R1* ($q = 0.002$, $p = 0.02$) and *Pka-C1* ($q = 0.002$, $p = 0.005$), which encode a cyclic AMP-dependent protein kinase [27,71]; the calcium/calmodulin-dependent adenylate cyclase encoded by the *rutabaga* gene ($q = 0.008$, $p = 0.03$ [26]); and *sluggish A*, a glutamate biosynthesis enzyme [72].

Expression of only nine alcohol sensitive genes was not significant on our microarray, including: the gene encoding tyramine β -hydroxylase ($p = 0.23$), an enzyme required for the synthesis of octopamine [24,71]; the gene encoding GABA-B receptor-1 ($p = 0.53$) [73]; *hangover* ($p = 0.52$), which encodes a nucleic acid binding zinc finger protein and has been implicated in both the response to heat stress and the induction of ethanol tolerance [24]; and *homer* ($p = 0.18$), which is required for behavioral plasticity [74] - mutant flies exhibit both increased sensitivity to the sedative effects of ethanol and failure to develop normal levels of rapid tolerance [75]. Taken together, around 70% of already implicated genes in alcohol sensitivity were found to be differentially expressed on our microarray.

Other notable probe sets with altered transcriptional regulation include *Sorbitol dehydrogenase 2*, *CG3523*, *CG16935* and *v(2)ko5816*, all of which encode products with alcohol dehydrogenase activity. A previous study reported that mutants in *white rabbit* ($p = 0.23$), which encodes *RhoGAP18B* ($q = 0.009$, $p = 0.04$), are resistant to the sedating effects of ethanol [29]. In our study six probe sets that encode *RhoGap* gene family members (*RhoGAP19D*, *54D*, *16F*, *100F* and *71E*) showed changes in expression levels in response to ethanol selection ($q < 0.001$). Furthermore, 22 of the genes with changes in transcript levels on our microarrays corresponded to genes differentially expressed in the frontal

cortex [9] and 10 genes from prefrontal cortex and nucleus accumbens of alcoholics [7] (Additional data file 11).

In addition to human orthologues associated with alcoholism, 246 genes with altered transcript abundance on our microarrays correspond to murine orthologues implicated in altered transcriptional regulation in a meta-analysis study of alcohol drinking preference in mice [3]. *Acetyl Coenzyme A synthase*, *Aldh*, *Beadex*, *CG16935*, *Fdh*, *Laminin B2*, *lethal (2) essential for life* and *lethal(1)G0007* were among those genes (Additional data file 12). In addition, several *Drosophila* transcripts that are differentially expressed in response to artificial selection have murine orthologues associated with alcohol related phenotypes (Additional data file 12), including *Aldehyde dehydrogenase family 6 member*, which maps to a region on 14q24.23 implicated in alcoholism [76], *Carnitine palmitoyl-transferase 1*, *Cathepsin B*, *Distal-less homeobox 1*, *Glutamate oxaloacetate transaminase 2*, *Dorsal switch protein 1* and *synapsin* [17,77,78].

Flies can readily be grown in large numbers in defined genetic backgrounds under controlled environmental conditions and alcohol sensitivity can be quantified precisely. Our results consolidate the notion that *Drosophila melanogaster* can serve as a gene discovery tool for candidate genes that predispose to alcohol related phenotypes in the human population, and demonstrate the power of transcriptional profiling of selection lines derived from a common base population as a complementary approach for identifying candidate genes for complex traits.

Materials and methods

Drosophila stocks

Flies were reared on cornmeal/molasses/agar medium under standard culture conditions (25°C, 12:12 hour light/dark cycle). Behavioral assays were conducted in a behavioral chamber (25°C, 70% humidity) between 9 am and 12 am, with the exception of the alcohol selection assays, which were done between 9 am and 2 pm at room temperature. Flies were not exposed to CO₂ anesthesia for at least 24 hours prior to the assay. Homozygous *P*-element insertion lines containing *P[GT1]*-elements in or near candidate genes in the co-isogenic *Canton S B* background were generated by Dr Hugo Bellen (Baylor College of Medicine, Houston, TX, USA) as part of the Berkeley *Drosophila* Genome Project [50].

Quantitative assay for alcohol sensitivity

To quantify alcohol sensitivity, we placed flies ($N = 60-70$) in an inebriometer pre-equilibrated with ethanol vapor from which they were eluted at one minute intervals. The MET is a measure of alcohol sensitivity [79].

Artificial selection for alcohol sensitivity

The base population was generated from 60 isofemale lines established from flies collected in Raleigh, NC in 1999. The

isofemale lines were crossed in a round robin design (line 1 ♀ × line 2 ♂, line 2 ♀ × line 3 ♂, ... line 60 ♀ × line 1 ♂). Single fertilized females from each cross were placed in each of two culture bottles. In the following generation (G₀), the alcohol sensitivity of 60 males and 60 virgin females of each replicate was scored using the alcohol sensitivity assay. The 20 most resistant flies (males and females) from each replicate were placed in bottles to initiate the two resistant lines (R₁, R₂); and the 20 sensitive flies from each replicate initiated the two sensitive lines (S₁, S₂). The two control lines were initiated with the remaining 20 flies (C₁, C₂). In the following (G₁) and all subsequent generations, the same procedure was repeated: 60 males and females, separately, from each line (resistant, sensitive, and control) were scored, and the 20 highest-scoring flies from the resistant lines and the 20 lowest-scoring flies from the sensitive lines were selected as parents for the next generation. Control line flies were scored each generation and 20 random flies were used as parents.

Estimates of realized heritability (h^2) were calculated by regression of the cumulative selection response (ΣR) on the cumulative selection differential (ΣS) [80].

Correlated responses to selection

To assess the specificity of the selection response, we tested our selected lines for a battery of other traits: locomotor, aggressive, and olfactory behavior, and starvation resistance.

Locomotor behavior was assessed using two different assays. Locomotor reactivity was assessed as described previously [33]. A single three- to five-day-old fly was placed in a vial with approximately 3 ml standard medium, and subjected to gentle mechanical disturbance by tapping on the bench top. The vial was placed horizontally, and the total amount of time the fly remained mobile for a 45 second period immediately following the disturbance was the locomotor reactivity score of the individual. This assay was performed at generation 35, with 20 replicate measurements per line per sex. In the second climbing assay, individual flies were transferred without anesthesia into an empty glass vial, with the height of the vial demarcated in 5 mm intervals from 0 to 27. The fly was tapped to the bottom of the vial, which was then placed vertically. The climbing score was the maximum height reached within the eight second observation period. Twenty replicates per line per sex were tested at generation 36.

Aggressive behavior was assessed as previously described [32]. Aggression of single individuals was quantified by placing one experimental male, with wild-type eye color, with three reference white-eyed isogenic w^{1118} *Canton-S* males. The flies were placed in a vial without food for 90 minutes, after which they were transferred (without anesthesia) to a test arena containing a droplet of food and allowed to acclimate for two minutes. After the acclimation period, the flies were observed for two minutes. The following behaviors were scored as aggressive encounters: kicking, chasing, wing-rais-

ing and boxing [81]. The score of the experimental fly was the number of encounters in which it exhibited an aggressive behavior, including interactions initiated by the experimental fly and those in which he responded aggressively to a reference fly. Thirty replicates per line per sex were tested at generation 36.

The olfactory behavior assay was performed as described previously [82]. The flies were placed in a vial without food for 60 minutes and after that were screened by quantifying olfactory avoidance behavior. Five flies per replicate with 15 replicates per sex per line at a concentration of 0.1% (v/v), 0.3% (v/v) and 1% (v/v) benzaldehyde were tested between 9.00 am and 1.00 pm, in a randomized design, in which measurements on individual lines were collected over multiple days to average environmental variation.

Starvation resistance was assessed as previously described [55]. Single sex groups of ten two-day-old flies were placed in vials containing non-nutritive media (1.5% agar and 5 ml water). Survival was scored every eight hours. This assay was conducted at generation 37, with five replicate measurements per line per sex.

Statistical analysis of correlated responses

Differences between the selection lines for the correlated traits were assessed using a nested mixed model analysis of variance (ANOVA):

$$Y = \mu + Selection + Line (Selection) + Sex + Selection \times Sex + Line (Selection) \times Sex + \varepsilon$$

where Y is the phenotypic score, μ is the overall mean, *Selection* is the fixed effect of the selection treatment (resistant, control, or sensitive), *Line (Selection)* is the random effect of the replicate within each selection group, *Sex* is the fixed effect of sex, and ε is the error variance. The terms of most interest in the model are *Selection* and *Line (Selection)*. A significant *Selection* term is indicative of a correlated response in the trait being tested to selection for alcohol sensitivity. The *Line (Selection)* term reveals whether replicate lines responded similarly or divergently, allowing an assessment of the effects of random genetic drift within a replicate line.

DNA extraction, PCR amplification, restriction digestion

Genomic DNA was extracted from 20 adult males and 20 adult females individually of each selection line using Puregene *DNA purification system* (Gentra systems, Minneapolis, MN, USA). PCR amplification was performed on 100 ng of DNA from each line. The primers were *Adh*-forward 5'CAACATTGGATCCGTCCTACTG' (1,355 bp) and *Adh*-reverse 5'GCTCAACATCCAACCAGGAG' (1,623 bp). The basic PCR conditions were 35 cycles of denaturation at 94°C for 30 s, annealing at 56°C for 30 s and extension at 72°C for 30 s with 1 unit of *RedTaq* DNA polymerase (Sigma-Aldrich,

Carlsband, CA, USA). The 269 bp product was then digested for 3 hours using HpyCH4 IV enzyme (New England BioLabs, Ipswich, MA, USA), according to the supplier's instructions. The A-C polymorphism at position 1,490 bp is responsible for the Lys - Thr substitution between Fast and Slow *Adh* alleles [47]. The HpyCH4 IV enzyme recognized the A/CGT nucleotide sequence corresponding to the Slow allele, yielding 240 bp and 29 bp restriction fragments that could be separated by electrophoresis from the 269 bp fragment of the Fast allele.

Whole genome expression analysis

At generation 25, two replicates of 15 three- to five-day-old virgin males and females were collected from each selection line. Total RNA was extracted from the 24 samples (six lines \times two sexes \times two replicates) using the Trizol reagent (Gibco BRL, Gaithersburg, MD, USA). Biotinylated cRNA probes were hybridized to high density oligonucleotide microarrays (Affymetrix, Inc. Drosophila GeneChip 2.0) and visualized with a streptavidin-phycoerythrin conjugate, as described in the Affymetrix GeneChip Expression Analysis Technical Manual (2000), using internal references for quantification. The quantitative estimate of expression of each probe set is the *Signal (Sig)* metric, as described in the Affymetrix Microarray Suite, Version 5.0.

Microarray data analysis

The 18,800 probe sets on the Affymetrix Drosophila GeneChip 2.0 are represented by 14 perfect-match (PM) and 14 mismatch (MM) pairs. The *Sig* metric is computed using the weighted log(PM-MM) intensity for each probe set, and was scaled to a median intensity of 500. A detection call of Present, Absent, or Marginal is also reported for each probe set. We excluded probe sets with more than half of the samples called 'Absent' from the analysis, leaving 11,838 probe sets. This filter retained sex-specific transcripts but eliminated probe sets with very low and/or variable expression levels [31]. On the remaining probe sets, we conducted two-way fixed effect ANOVAs of the Signal metric, using the following model:

$$Y = \mu + Line + Sex + Line \times Sex + \varepsilon$$

where *Sex* and *Line* are the fixed effects of sex and selection line and ε is the variance between replicate arrays. We corrected the p values computed in these ANOVAs for multiple tests using a stringent false discovery rate criterion of $q < 0.001$. We used contrast statements [31] to assess whether expression levels of probe sets with L and/or $S \times L$ terms at or below the $q = 0.001$ threshold were significantly different between selection groups (resistant, control, and sensitive) at the $p < 0.05$ level, both within each sex and pooled across sexes. All statistical analyses were performed using SAS procedures [29,83]. GO categories were annotated using Affymetrix [84] and FlyBase [85] compilations.

Functional tests of mutations in candidate genes

We tested whether 37 mutations in 35 of the candidate genes with altered transcript abundance between the selection lines affected alcohol sensitivity. The mutations were homozygous *P[GT1]* elements inserted within the candidate genes, and all were generated in a common co-isogenic background (*Canton S*, B background) [50]. Alcohol sensitivity was assessed for all mutant lines (4-5 replicates/line, $N = 60-70$, 3- to 5-day-old males/replicate) using an inebriometer [79]. We used analysis of variance to assess whether the sensitivity of *P*-element insertion lines differed significantly from the control, according to the model:

$$Y = \mu + \text{Line} + \text{Replicate}(\text{Line}) + \varepsilon$$

where μ is the overall mean, *Line* is the fixed effect of line (*P*-element insertion versus Control), *Replicate* is the random effect of replicate, nested within line, and ε is the variance within replicates. A significant *Line* term suggests that the mutant is significantly different from the control.

Abbreviations

Adh, Alcohol dehydrogenase; C, control line; GO, gene ontology; MET, mean elution time; R, resistant line; S, sensitive line.

Authors' contributions

TVM, RRHA and TFCM conceived and designed the experiments. TVM performed the experiments. TVM and TFCM analyzed the data. TVM, RRHA and TFCM wrote the paper. All authors read and approved the final manuscript.

Additional data files

The following additional data are available with the online version of this paper. Additional data file 1 contains a list of probe sets differentially expressed between selection lines at $q < 0.001$. Additional data file 2 contains a list of probe sets with significant differences in contrast statements at $p < 0.05$. Additional data file 3 contains a list of 121 probe sets with larger than two-fold differences in transcript abundance between selection lines. Additional data file 4 contains biological processes GO categories of genes in Additional data file 3. Additional data file 5 contains biological processes GO categories of genes in Additional data file 2. Additional data file 6 contains molecular function GO categories of genes in Additional data file 2. Additional data file 7 contains a list of common probe sets of differentially expressed genes from three artificially selected populations. Additional data file 8 contains biological processes GO categories of genes in Additional data file 7. Additional data file 9 contains a list of common probe sets differentially expressed in response to exposure to ethanol in two experiments (artificial selection for alcohol sensitivity/resistant and tolerance development).

Additional data file 10 contains a list of genes previously implicated in alcohol sensitivity in *Drosophila melanogaster*. Additional data file 11 contains a list of *Drosophila* probe sets of genes with human orthologues differentially expressed in alcoholics' brain regions. Additional data file 12 contains a list of *Drosophila* probe sets of genes that are differentially expressed in response to artificial selection and have murine orthologues associated with alcohol related phenotypes.

Acknowledgements

We thank Jennifer Foss and Paul Gilligan for technical assistance, TJ Morgan for advice with data analysis, and MJ Zanis for his Perl programming skills. This work was supported by grants from the National Institutes of Health (to RRHA and TFCM). This is a publication of the WM Keck Center for Behavioral Biology.

References

- Shalala D: **Protecting research subjects - what must be done.** *N Engl J Med* 2000, **343**:808-810.
- Radel M, Goldman D: **Pharmacogenetics of alcohol response and alcoholism: the interplay of genes and environmental factors in thresholds for alcoholism.** *Drug Metab Dispos* 2001, **29**:489-494.
- Mulligan CJ, Robin RW, Osier MV, Sambuughin N, Goldfarb LG, Kittles RA, Hesselbrock D, Goldman D, Long JC: **Allelic variation at alcohol metabolism genes (ADH1B, ADH1C, ALDH2) and alcohol dependence in an American Indian population.** *Hum Genet* 2003, **113**:325-336.
- Sinha R, Cloninger CR, Parsian A: **Linkage disequilibrium and haplotype analysis between serotonin receptor 1B gene variations and subtypes of alcoholism.** *Am J Med Genet B Neuropsychiatr Genet* 2003, **121**:83-88.
- Goldman D, Oroszi G, Ducci F: **The genetics of addictions: uncovering the genes.** *Nat Rev Genet* 2005, **6**:521-532.
- Lewohl JM, Wang L, Miles MF, Zhang L, Dodd PR, Harris RA: **Gene expression in human alcoholism: microarray analysis of frontal cortex.** *Alcohol Clin Exp Res* 2000, **24**:1873-1882.
- Flatscher-Bader T, van der Brug M, Hwang JW, Gochee PA, Matsumoto I, Niwa S, Wilce PA: **Alcohol-responsive genes in the frontal cortex and nucleus accumbens of human alcoholics.** *J Neurochem* 2005, **93**:359-370.
- Liu J, Lewohl JM, Dodd PR, Randall PK, Harris RA, Mayfield RD: **Gene expression profiling of individual cases reveals consistent transcriptional changes in alcoholic human brain.** *J Neurochem* 2004, **90**:1050-1058.
- Liu J, Lewohl JM, Harris RA, Iyer VR, Dodd PR, Randall PK, Mayfield RD: **Patterns of gene expression in the frontal cortex discriminate alcoholic from nonalcoholic individuals.** *Neuropsychopharmacology* 2006, **31**:1574-1582.
- Mayfield RD, Lewohl JM, Dodd PR, Herlihy A, Liu J, Harris RA: **Patterns of gene expression are altered in the frontal and motor cortices of human alcoholics.** *J Neurochem* 2002, **81**:802-813.
- Worst TJ, Tan JC, Robertson DJ, Freeman WM, Hyytia P, Kiiannmaa K, Vrana KE: **Transcriptome analysis of frontal cortex in alcohol-preferring and nonpreferring rats.** *J Neurosci Res* 2005, **80**:529-538.
- Crabbe JC, Phillips TJ, Harris RA, Arends MA, Koob GF: **Alcohol-related genes: contributions from studies with genetically engineered mice.** *Addict Biol* 2006, **11**:195-269.
- Newton PM, Messing RO: **Intracellular signaling pathways that regulate behavioral responses to ethanol.** *Pharmacol Ther* 2006, **109**:227-237.
- Wand G, Levine M, Zweifel L, Schwindinger W, Abel T: **The cAMP-protein kinase A signal transduction pathway modulates ethanol consumption and sedative effects of ethanol.** *J Neurosci* 2001, **21**:5297-5303.
- Yaka R, Phamluong K, Ron D: **Scaffolding of Fyn kinase to the NMDA receptor determines brain region sensitivity to ethanol.** *J Neurosci* 2003, **23**:3623-3632.
- Yaka R, Tang KC, Camarini R, Janak PH, Ron D: **Fyn kinase and**

- NR2B-containing NMDA receptors regulate acute ethanol sensitivity but not ethanol intake or conditioned reward.** *Alcohol Clin Exp Res* 2003, **27**:1736-1742.
17. Daniels GM, Buck KJ: **Expression profiling identifies strain-specific changes associated with ethanol withdrawal in mice.** *Genes Brain Behav* 2002, **1**:35-45.
 18. Guarnieri DJ, Heberlein U: **Drosophila melanogaster, a genetic model system for alcohol research.** *Int Rev Neurobiol* 2003, **54**:199-228.
 19. Morozova TV, Anholt RR, Mackay TF: **Transcriptional response to alcohol exposure in Drosophila melanogaster.** *Genome Biol* 2006, **7**:R95.
 20. Scholz H, Ramond J, Singh CM, Heberlein U: **Functional ethanol tolerance in Drosophila.** *Neuron* 2000, **28**:261-271.
 21. Rubin GM, Yandell MD, Wortman JR, Gabor Miklos GL, Nelson CR, Hariharan IK, Fortini ME, Li PW, Apweiler R, Fleischmann W, et al.: **Comparative genomics of the eukaryotes.** *Science* 2000, **287**:2204-2215.
 22. Singh CM, Heberlein U: **Genetic control of acute ethanol-induced behaviors in Drosophila.** *Alcohol Clin Exp Res* 2000, **24**:1127-1136.
 23. Wolf FW, Rodan AR, Tsai LT, Heberlein U: **High-resolution analysis of ethanol-induced locomotor stimulation in Drosophila.** *J Neurosci* 2002, **22**:11035-11044.
 24. Scholz H, Franz M, Heberlein U: **The hangover gene defines a stress pathway required for ethanol tolerance development.** *Nature* 2005, **436**:845-847.
 25. Cheng Y, Endo K, Wu K, Rodan AR, Heberlein U, Davis RL: **Drosophila fasciclin II is required for the formation of odor memories and for normal sensitivity to alcohol.** *Cell* 2001, **105**:757-768.
 26. Moore MS, DeZazzo J, Luk AY, Tully T, Singh CM, Heberlein U: **Ethanol intoxication in Drosophila: Genetic and pharmacological evidence for regulation by the cAMP signaling pathway.** *Cell* 1998, **93**:997-1007.
 27. Park SK, Sedore SA, Cronmiller C, Hirsh J: **Type II cAMP-dependent protein kinase-deficient Drosophila are viable but show developmental, circadian, and drug response phenotypes.** *J Biol Chem* 2000, **275**:20588-20596.
 28. Spanagel R, Pendyala G, Abarca C, Zghoul T, Sanchis-Segura C, Magno MC, Lascorz J, Depner M, Holzberg D, Soyka M, et al.: **The clock gene Per2 influences the glutamatergic system and modulates alcohol consumption.** *Nat Med* 2005, **11**:35-42.
 29. Rothenfluh A, Threlkeld RJ, Bainton RJ, Tsai LT, Lasek AW, Heberlein U: **Distinct behavioral responses to ethanol are regulated by alternate RhoGAP18B isoforms.** *Cell* 2006, **127**:199-211.
 30. Tabakoff B, Bhave SV, Hoffman PL: **Selective breeding, quantitative trait locus analysis, and gene arrays identify candidate genes for complex drug-related behaviors.** *J Neurosci* 2003, **23**:4491-4498.
 31. Mackay TF, Heinsohn SL, Lyman RF, Moehring AJ, Morgan TJ, Rollmann SM: **Genetics and genomics of Drosophila mating behavior.** *Proc Natl Acad Sci USA* 2005, **102**(Suppl 1):6622-6629.
 32. Edwards AC, Rollmann SM, Morgan TJ, Mackay TF: **Quantitative genomics of aggressive behavior in Drosophila melanogaster.** *PLoS Genet* 2006, **2**:e154.
 33. Jordan KW, Carbone MA, Yamamoto A, Morgan TJ, Mackay TF: **Quantitative genomics of locomotor behavior in Drosophila melanogaster.** *Genome Biol* 2007, **8**:R172.
 34. Cherek DR, Spiga R, Egli M: **Effects of response requirement and alcohol on human aggressive responding.** *J Exp Anal Behav* 1992, **58**:577-587.
 35. Graham K, Leonard KE, Room R, Wild TC, Pihl RO, Bois C, Single E: **Current directions in research on understanding and preventing intoxicated aggression.** *Addiction* 1998, **93**:659-676.
 36. Wells S, Graham K, Speechley M, Koval JJ: **Drinking patterns, drinking contexts and alcohol-related aggression among late adolescent and young adult drinkers.** *Addiction* 2005, **100**:933-944.
 37. Gilliam DM, Collins AC: **Quantification of physiological and behavioral measures of alcohol withdrawal in long-sleep and short-sleep mice.** *Alcohol Clin Exp Res* 1986, **10**:672-678.
 38. Lieber CS: **Alcoholic fatty liver: its pathogenesis and mechanism of progression to inflammation and fibrosis.** *Alcohol* 2004, **34**:9-19.
 39. Montooth KL, Siebenthal KT, Clark AG: **Membrane lipid physiology and toxin catabolism underlie ethanol and acetic acid tolerance in Drosophila melanogaster.** *J Exp Biol* 2006, **209**:3837-3850.
 40. Whitfield JB: **ADH and ALDH genotypes in relation to alcohol metabolic rate and sensitivity.** *Alcohol Alcohol Suppl* 1994, **2**:59-65.
 41. Whitfield JB, Martin NG: **Alcohol consumption and alcohol pharmacokinetics: interactions within the normal population.** *Alcohol Clin Exp Res* 1994, **18**:238-243.
 42. McDonald JF, Anderson SM, Santos M: **Biochemical differences between products of the Adh locus in Drosophila.** *Genetics* 1980, **95**:1013-1022.
 43. Oakeshott JG, Gibson JB, Wilson SR: **Selective effects of the genetic background and ethanol on the alcohol dehydrogenase polymorphism in Drosophila melanogaster.** *Heredity* 1984, **53**:51-67.
 44. Chambers GK, Wilks AV, Gibson JB: **Variation in the biochemical properties of the Drosophila alcohol dehydrogenase allozymes.** *Biochem Genet* 1984, **22**:153-168.
 45. Laurie CC, Bridgham JT, Choudhary M: **Associations between DNA sequence variation and variation in expression of the Adh gene in natural populations of Drosophila melanogaster.** *Genetics* 1991, **129**:489-499.
 46. Laurie CC, Stam LF: **Quantitative analysis of RNA produced by slow and fast alleles of Adh in Drosophila melanogaster.** *Proc Natl Acad Sci USA* 1988, **85**:5161-5165.
 47. Kreitman M: **Nucleotide polymorphism at the alcohol dehydrogenase locus of Drosophila melanogaster.** *Nature* 1983, **304**:412-417.
 48. **NCBI Gene Expression Omnibus** [<http://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE7614>]
 49. Storey JD, Tibshirani R: **Statistical significance for genomewide studies.** *Proc Natl Acad Sci USA* 2003, **100**:9440-9445.
 50. Bellen HJ, Levis RW, Liao G, He Y, Carlson JW, Tsang G, Evans-Holm M, Hiesinger PR, Schulze KL, Rubin GM, et al.: **The BDGP gene disruption project: single transposon insertions associated with 40% of Drosophila genes.** *Genetics* 2004, **167**:761-781.
 51. Lukacsovich T, Asztalos Z, Awano W, Baba K, Kondo S, Niwa S, Yamamoto D: **Dual-tagging gene trap of novel genes in Drosophila melanogaster.** *Genetics* 2001, **157**:727-742.
 52. Barbancho M, Sanchez-Canete FJ, Dorado G, Pineda M: **Relation between tolerance to ethanol and alcohol dehydrogenase (ADH) activity in Drosophila melanogaster: selection, genotype and sex effects.** *Heredity* 1987, **58**:443-450.
 53. Mercot H, Massaad L: **ADH activity and ethanol tolerance in third chromosome substitution lines in Drosophila melanogaster.** *Heredity* 1989, **62**:35-44.
 54. Kerver JW, Wolf W, Kamping A, van Delden W: **Effects on ADH activity and distribution, following selection for tolerance to ethanol in Drosophila melanogaster.** *Genetica* 1992, **87**:175-183.
 55. Harbison ST, Chang S, Kamdar KP, Mackay TF: **Quantitative genomics of starvation stress resistance in Drosophila.** *Genome Biol* 2005, **6**:R36.
 56. Bokor K, Pecsénye K: **Strains of Drosophila melanogaster differ in alcohol tolerance.** *Hereditas* 1997, **126**:103-113.
 57. Pecsénye K, Lefkovich LP, Giles BE, Saura A: **Differences in environmental temperature, ethanol and sucrose associated with enzyme activity and weight changes in Drosophila melanogaster.** *Insect Biochem Mol Biol* 1996, **26**:135-145.
 58. Bainton RJ, Tsai LTY, Singh CM, Moore MS, Neckameyer WS, Heberlein U: **Dopamine modulates acute responses to cocaine, nicotine and ethanol in Drosophila.** *Curr Biol* 2000, **10**:187-194.
 59. Wen T, Parrish CA, Xu D, Wu Q, Shen P: **Drosophila neuropeptide F and its receptor, NPFRI, define a signaling pathway that acutely modulates alcohol sensitivity.** *Proc Natl Acad Sci USA* 2005, **102**:2141-2146.
 60. Heberlein U, England B, Tjian R: **Characterization of Drosophila transcription factors that activate the tandem promoters of the alcohol dehydrogenase gene.** *Cell* 1985, **41**:965-977.
 61. Fry JD, Saweikis M: **Aldehyde dehydrogenase is essential for both adult and larval ethanol resistance in Drosophila melanogaster.** *Genet Res* 2006, **87**:87-92.
 62. Lissimore JL, Baumgardner CA, Geer BW, Sullivan DT: **Effect of dietary carbohydrates and ethanol on expression of genes encoding sn-glycerol-3-phosphate dehydrogenase, aldolase, and phosphoglycerate kinase in Drosophila larvae.** *Biochem Genet* 1990, **28**:615-630.
 63. Pecsénye K, Bokor K, Lefkovich LP, Giles BE, Saura A: **Enzymatic responses of Drosophila melanogaster to long- and short-term exposures to ethanol.** *Mol Gen Genet* 1997, **255**:258-268.

64. Shiraiwa T, Nitasaka E, Yamazaki T: **Geko, a novel gene involved in olfaction in *Drosophila melanogaster***. *J Neurogenet* 2000, **14**:145-164.
65. Cowmeadow RB, Krishnan HR, Atkinson NS: **The slowpoke gene is necessary for rapid ethanol tolerance in *Drosophila***. *Alcohol Clin Exp Res* 2005, **29**:1777-1786.
66. Cowmeadow RB, Krishnan HR, Ghezzi A, Al'Hasan YM, Wang YZ, Atkinson NS: **Ethanol tolerance caused by slowpoke induction in *Drosophila***. *Alcohol Clin Exp Res* 2006, **30**:745-753.
67. Davis RL, Kiger JA Jr: **Dunce mutants of *Drosophila melanogaster*: mutants defective in the cyclic AMP phosphodiesterase enzyme system**. *J Cell Biol* 1981, **90**:101-107.
68. Zhang HG, French-Constant RH, Jackson MB: **A unique amino acid of the *Drosophila* GABA receptor with influence on drug sensitivity by two mechanisms**. *J Physiol* 1994, **479**:65-75.
69. Zhang HG, Lee HJ, Rocheleau T, French-Constant RH, Jackson MB: **Subunit composition determines picrotoxin and bicuculline sensitivity of *Drosophila* gamma-aminobutyric acid receptors**. *Mol Pharmacol* 1995, **48**:835-840.
70. Kim MS, Repp A, Smith DP: **LUSH odorant-binding protein mediates chemosensory responses to alcohols in *Drosophila melanogaster***. *Genetics* 1998, **150**:711-721.
71. Rothenfluh A, Heberlein U: **Drugs, flies, and videotape: the effects of ethanol and cocaine on *Drosophila* locomotion**. *Curr Opin Neurobiol* 2002, **12**:639-645.
72. Garfinkel M, Fu CH, Venglarik CJ, Ruden DM: **Increased resistance to ethanol intoxication conferred by a mutation in the *Drosophila* structural gene for proline dehydrogenase (*sigA*), a glutamate biosynthesis enzyme**. *A Dros Res Conf* 2003, **44**:834C.
73. Dzitoyeva S, Dimitrijevic N, Manev H: **Gamma-aminobutyric acid B receptor I mediates behavior-impairing actions of alcohol in *Drosophila*: adult RNA interference and pharmacological evidence**. *Proc Natl Acad Sci USA* 2003, **100**:5485-5490.
74. Diagana TT, Thomas U, Prokopenko SN, Xiao B, Worley PF, Thomas JB: **Mutation of *Drosophila homer* disrupts control of locomotor activity and behavioral plasticity**. *J Neurosci* 2002, **22**:428-436.
75. Urizar NL, Yang Z, Edenberg HJ, Davis RL: ***Drosophila homer* is required in a small set of neurons including the ellipsoid body for normal ethanol sensitivity and tolerance**. *J Neurosci* 2007, **27**:4541-4551.
76. Wyszynski DF, Panhuysen CI, Ma Q, Yip AG, Wilcox M, Erlich P, Farrer LA: **Genome-wide screen for heavy alcohol consumption**. *BMC Genet* 2003, **4**(Suppl 1):S106.
77. Kerns RT, Ravindranathan A, Hassan S, Cage MP, York T, Sikela JM, Williams RW, Miles MF: **Ethanol-responsive brain region expression networks: implications for behavioral responses to acute ethanol in DBA/2J versus C57BL/6J mice**. *J Neurosci* 2005, **25**:2255-2266.
78. Rodd ZA, Bertsch BA, Strother WN, Le-Niculescu H, Balaraman Y, Hayden E, Jerome RE, Lumeng L, Nurnberger JI Jr, Edenberg HJ, et al.: **Candidate genes, pathways and mechanisms for alcoholism: an expanded convergent functional genomics approach**. *Pharmacogenomics J* 2007, **7**:222-256.
79. Weber KE: **An apparatus for measurement of resistance to gas-phase reagents**. *Drosophila Inform Serv* 1988, **67**:90-92.
80. Falconer DS, Mackay TFC: *Introduction to Quantitative Genetics* 4th edition. Addison Wesley Longman, Harlow, Essex, UK; 1996.
81. Chen S, Lee AY, Bowens NM, Huber R, Kravitz EA: **Fighting fruit flies: a model system for the study of aggression**. *Proc Natl Acad Sci USA* 2002, **99**:5664-5668.
82. Anholt RR, Lyman RF, Mackay TF: **Effects of single P-element insertions on olfactory behavior in *Drosophila melanogaster***. *Genetics* 1996, **143**:293-301.
83. SAS Institute: *SAS/STAT User's Guide; Release 6.12* Cary, NC: SAS Institute; 1988.
84. **Affymetrix: Netaffx Analysis Center** [<http://www.affymetrix.com>]
85. Drysdale RA, Crosby MA, FlyBase Consortium: **FlyBase: genes and gene models**. *Nucleic Acids Res* 2005, **33**(Database issue):D390-395.
86. Remm M, Storm CE, Sonnhammer EL: **Automatic clustering of orthologs and in-paralogs from pairwise species comparisons**. *J Mol Biol* 2001, **314**:1041-1052.