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14. ABSTRACT <p>Neurofibromatosis type 1 (NF1) is a genetic condition which affects one in 3,000 children and is known mostly because it causes light-brown patches of skin pigment, called café-au-lait spots, but also tumors that grow along nerves, called neurofibroma. A second aspect of NF1 is that the majority of children with NF1 develop cognitive deficits. The disorder is caused by mutations in a gene neurofibromin. In normal individuals, neurofibromin regulates the activity of another protein, called Ras, which controls cell divisions. In NF1 patients, the faulty neurofibromin gene fails to regulate Ras, which then tells cells to divide without stopping.</p> <p>Fortunately, only rarely do these tumors progress into malignant tumors. In contrast to the well understood mechanisms by which mutant neurofibromin fails to regulate Ras and hence cell divisions, why and how mutant neurofibromin leads to very prevalent learning disabilities is not well understood. Although the severity can vary widely from patient to patient, the majority of children with NF1 (up to 70%) have cognitive deficits, mostly attention deficits and learning disabilities. The long-term goals of this research grant proposal are to determine the mechanisms by which neurofibromin regulates learning, and to identify new drugs capable to antagonize learning deficits in an NF1 animal model.</p>					
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1. INTRODUCTION:

Neurofibromatosis type 1 (NF1) is a neurogenetic disorder best known to cause predisposition to central and peripheral nervous system tumors. At the same time, NF1 causes significant cognitive impairments, and 50-70% of children with NF1 exhibit cognitive dysfunction, most prominently scholastic under-performance characterized by attention deficit and learning disabilities. The NF1 protein governs distinct aspects of cognitive behavior: the NF1-GRD attenuates Ras-pathway and GABA signaling to regulate memory, while the NF1 C-terminal region activates adenylyl cyclase-mediated cAMP homeostasis to govern learning. Despite clear evidence of cAMP-mediated learning in *Drosophila Nf1* models, it is unclear whether NF1-dependent cAMP signaling is critical for vertebrate learning and/or memory. The aims of this proposal are to take advantage of the zebrafish system to 1) determine whether cAMP signaling contributes to NF1-dependent learning and memory in vertebrates and 2) identify compounds that attenuate the learning deficiency in NF1 through screening libraries of bioactive small molecules.

2. KEY WORDS:

Neurofibromatosis; zebrafish; NF1; cAMP; Ras; learning; memory

3. ACCOMPLISHMENTS:

What were the major goals of the project?

Specific Aim 1: Determine whether cAMP signaling is critical for NF1 dependent learning and memory in vertebrates. This Aim has been completed, see below.

Specific Aim 2: Identify chemical modifiers of *Nf1* dependent learning. Work on this Aim is about to begin.

What was accomplished under these goals?

We successfully completed Specific Aim 1 to determine whether cAMP signaling is critical for NF1 dependent learning and memory in vertebrates. The results of this Aim have been published in a paper entitled '*Modulation of cAMP and Ras Signaling Pathways Improves Distinct Behavioral Deficits in a Zebrafish Model of Neurofibromatosis Type 1*' (**Cell Reports** 8, 1265–1270; 2014). In brief, we show that *nf1*-deficient zebrafish exhibit learning and memory deficits and that acute pharmacological inhibition of downstream targets of Ras restores memory consolidation and recall but not learning. Conversely, acute pharmacological enhancement of cAMP signaling restores learning but not memory. Our data provide compelling evidence that *nf1* regulates learning and memory by distinct molecular pathways in vertebrates and that deficits produced by genetic loss of function are reversible. These findings support the investigation of cAMP signaling enhancers as a companion therapy to Ras inhibition in the treatment of cognitive dysfunction in NF1. Rather than providing data and graphs here we have included a copy of the paper in the appendix.

What opportunities for training and professional development has the project provided?

The postdoctoral fellow Dr. Kurt Marsden completed an IDP which served as a basis to openly discuss his achievements, plans to further develop their skills, and to prepare him for applying for academic positions. In addition, Dr. Marsden was my lab assistant for a zebrafish course in Woods Hole in which I teach about the use of zebrafish for neuroscience research. This course is a hands-on course for 22 students (faculty, postdocs and PhD students). In addition to gaining experience in teaching, Dr. Marsden interacted with all the other course faculty (~12), all leaders in the field.

How were the results disseminated to communities of interest?

Nothing to Report.

What do you plan to do during the next reporting period to accomplish the goals?

During the next funding period we will complete Specific Aim 2, to identify chemical modifiers of Nf1 dependent learning. Specifically, we will screen small molecule libraries to identify compounds that either increase or decrease learning in Nf1 mutant zebrafish.

4. IMPACT:

What was the impact on other disciplines?

Nothing to Report.

What was the impact on technology transfer?

Nothing to Report.

What was the impact on society beyond science and technology?

Nothing to Report.

5. CHANGES/PROBLEMS

Significant changes in use or care of human subjects.

Nothing to Report.

Significant changes in use or care of vertebrate animals.

Nothing to Report.

Significant changes in use of biohazards and/or select agents.

Nothing to Report.

6. PRODUCTS.

Publications

Wolman, M.A, de Groh, E. D, McBride, S. M., Jongens, T. A., **Granato, M*** and Epstein, J.A*. Modulation of cAMP and Ras signaling pathways improves distinct behavioral deficits in a zebrafish model of Neurofibromatosis type 1. *Cell reports*, 8(5):1265-70. *Co-senior authors.

Other Products

Press Release UPENN:

http://www.uphs.upenn.edu/news/News_Releases/2014/09/epstein/

Zebrafish Model of a Learning and Memory Disorder Shows Better Way to Target Treatment PHILADELPHIA — Using a zebrafish model of a human genetic disease called neurofibromatosis (NF1), a team from the [Perelman School of Medicine at the University of Pennsylvania](#) has found that the learning and memory components of the disorder are distinct features that will likely need different treatment approaches. They published their [results this month in Cell Reports](#).

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Name:	Michael Granato, Ph.D.
Project Role:	PI
Researcher Identifier:	n/a
Nearest person month worked:	1 Cal. Month
Contribution to Project:	Dr. Granato provided the intellectual framework and supervised this project.
Name:	Melissa Baxter
Project Role:	Technician
Researcher Identifier:	n/a
Nearest person month worked:	4 Cal. Months
Contribution to Project:	Ms. Baxter, replaced Hannah Bell (who left for Medical School), provided technical support, which includes maintaining fish stocks and generating embryos/larvae.
Name:	Hannah Bell
Project Role:	Technician
Researcher Identifier:	n/a
Nearest person month worked:	2 Cal. Months
Contribution to Project:	Ms. Bell provided technical support, which includes maintaining fish stocks and generating embryos/larvae.
Name:	Kurt C. Marsden, Ph.D.
Project Role:	Postdoctoral Researcher
Researcher Identifier:	n/a
Nearest person month worked:	4 Cal. Months
Contribution to Project:	Dr. Marsden performed some of the learning assays for Aim 1.

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

Nothing to Report.

What other organizations were involved as partners?

Nothing to Report.

8. SPECIAL REPORTING REQUIREMENTS

N/A

9. APPENDICES:

Wolman, M.A, de Groh, E. D, McBride, S. M., Jongens, T. A., **Granato, M*** and Epstein, J.A*. Modulation of cAMP and Ras signaling pathways improves distinct behavioral deficits in a zebrafish model of Neurofibromatosis type 1. *Cell reports*, 8(5):1265-70. ***Co-senior authors.**

Modulation of cAMP and Ras Signaling Pathways Improves Distinct Behavioral Deficits in a Zebrafish Model of Neurofibromatosis Type 1

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SUMMARY

Neurofibromatosis type 1 (NF1) is a common autosomal-dominant disorder associated with attention deficits and learning disabilities. The primary known function of neurofibromin, encoded by the *NF1* gene, is to downregulate Ras activity. We show that *nf1*-deficient zebrafish exhibit learning and memory deficits and that acute pharmacological inhibition of downstream targets of Ras (MAPK and PI3K) restores memory consolidation and recall but not learning. Conversely, acute pharmacological enhancement of cAMP signaling restores learning but not memory. Our data provide compelling evidence that neurofibromin regulates learning and memory by distinct molecular pathways in vertebrates and that deficits produced by genetic loss of function are reversible. These findings support the investigation of cAMP signaling enhancers as a companion therapy to Ras inhibition in the treatment of cognitive dysfunction in NF1.

INTRODUCTION

Neurofibromatosis type 1 (NF1) is associated with a broad range of clinical characteristics, including a predisposition to develop benign and malignant tumors, pigmentation defects, and cognitive deficits (Cichowski and Jacks, 2001). As many as 50%–70% of children with NF1 exhibit attention deficits and learning disabilities that contribute to scholastic underachievement and impaired social development (Hyman et al., 2005, 2006; Levine et al., 2006). Genetic and pharmacological experiments performed in mice and *Drosophila* support a role for the Ras-GTPase activating domain (GRD), which functions to downregulate Ras activity in protein-synthesis-dependent memory (Costa et al., 2002; Cui et al., 2008; Guilding et al., 2007; Ho et al., 2007; Li et al., 2005; Silva et al., 1997). However, cognitive dysfunction

in NF1 has been linked to mutations throughout the *NF1* gene that do not cluster in the region encoding the GRD, leading to the proposal that neurofibromin serves additional cellular functions (Fahsold et al., 2000). Studies performed in *Drosophila* suggest that neurofibromin can also stimulate adenylyl cyclase (AC), cAMP production, and PKA to promote learning and memory (Guo et al., 2000; Hannan et al., 2006; The et al., 1997; Tong et al., 2002). *Nf1*-deficient *Drosophila* brains show reduced cAMP levels, and expression of a C-terminal neurofibromin fragment lacking the GRD is sufficient to rescue learning (Ho et al., 2007; Tong et al., 2002). Similarly, brains of *Nf1*^{+/-} mice exhibit reduced cAMP levels (Brown et al., 2010, 2012; Hegedus et al., 2007) and cAMP regulation of dopaminergic function in the hippocampus is disrupted (Diggs-Andrews et al., 2013). The mechanism by which neurofibromin regulates AC remains controversial, and both Ras-dependent and Ras-independent pathways have been suggested (Guo et al., 1997; Hannan et al., 2006; Tong et al., 2002). Studies in *Drosophila* models of NF1 further argue that the resulting elevation in Ras activity, mediated through the upstream activation of neuronal dAkt, is responsible for observed decreases in cAMP signaling (Gouzi et al., 2011; Walker et al., 2006, 2013). Neurofibromin is also known to modulate both neural and glial development from neuroglial progenitors, and both Ras and cAMP have been implicated (Hegedus et al., 2007). Recent studies suggest that pharmacological activation of the cAMP pathway may enhance cognition in murine models (Jayachandran et al., 2014; Peng et al., 2014; Richter et al., 2013). However, it remains unclear whether NF1-dependent cAMP signaling is critical for learning or memory in vertebrates. Furthermore, the contributions of developmental and structural abnormalities to learning and memory deficits in NF1 have not yet been clearly defined (Armstrong et al., 2012; Karlsgodt et al., 2012; Shilyansky et al., 2010).

RESULTS AND DISCUSSION

We utilized a zebrafish model of NF1 that harbors null alleles in the *NF1* orthologs *nf1a* and *nf1b* (Shin et al., 2012) to evaluate molecular signaling pathways that control NF1-dependent

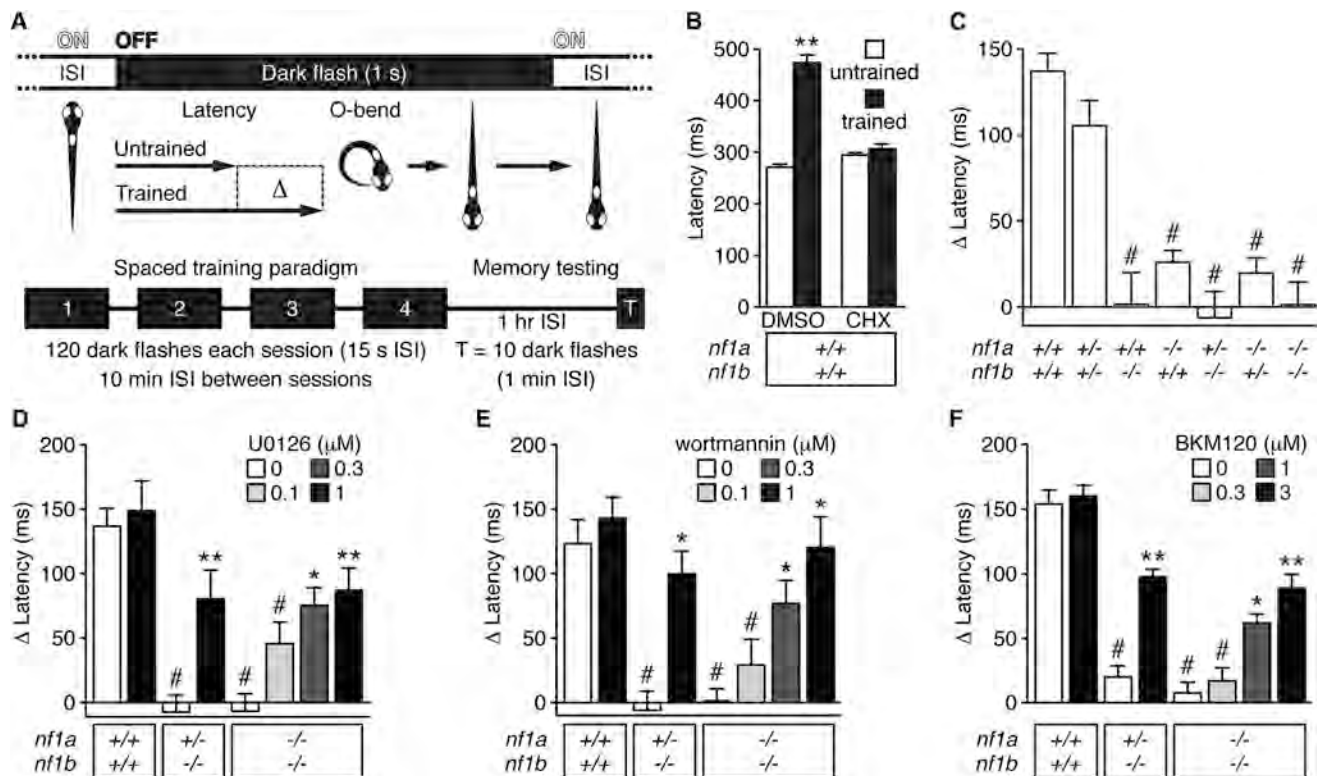


Figure 1. *nf1* Mutant Larvae Exhibit Reduced Memory Recall

(A) Schematic representation of the visual memory assay. ISI, interstimulus interval.

(B–F) Mean O-bend latency (B) or latency change (C–F) 1 hr after spaced training (test) versus untrained controls ($n = 26$ –130 O-bend maneuvers per genotype/treatment). # $p < 0.001$ versus wild-type untreated (C) or DMSO-treated (B and D–F) larvae. * $p < 0.01$, ** $p < 0.001$ versus same genotype, DMSO-treated larvae. One-way ANOVA. Error bars denote SEM.

See also [Figures S2](#) and [S3](#).

learning and memory in vertebrates. Larval zebrafish show a remarkable capacity for behavioral plasticity in response to visual and acoustic stimuli, including habituation (Roberts et al., 2013; Wolman et al., 2011), as evidenced by a progressive decline in responsiveness to repeated, inconsequential stimuli (Thompson and Spencer, 1966). The duration of habituated behavior provides a metric for nonassociative learning (short-term habituation) and memory formation and recall (long-term, protein-synthesis-dependent habituation). Importantly, habituation reflects a highly conserved form of attention-based learning and memory that is similar to the type of cognition impairment found in NF1 children (Hyman et al., 2005; Isenberg et al., 2013; Levine et al., 2006). We tested 5-day-old larvae for protein-synthesis-dependent visual habituation to evaluate memory formation and recall. After a period of light adaptation, exposing the larvae to a sudden absence of light, termed a dark flash, elicited a highly stereotyped yet habituable reorientation maneuver known as an O-bend (Movie S1; Burgess and Granato, 2007a). Delivering repetitive dark flashes through a spaced training paradigm elicited protein-synthesis-dependent memory formation (Figures 1A and 1B). One hour after training, wild-type larvae showed a near doubling in the latency time period before initiating an O-bend compared with responses prior to training (Figure 1B). Treatment with the protein synthesis

inhibitor cycloheximide (CHX, 10 μ M) abolished this increase (Figure 1B), consistent with a requirement for protein synthesis (Beck and Rankin, 1995; Davis and Squire, 1984). Larvae null for *nf1a* or *nf1b* showed impaired memory (Figure 1C). This memory deficit is consistent with cognitive impairment observed in NF1 patients and in other animal models of NF1, and supports the use of *nf1* mutant zebrafish to probe the mechanisms of NF1-dependent cognition.

Memory impairment in *Drosophila* and mouse NF1 models is due at least in part to elevated Ras signaling (Costa et al., 2002; Cui et al., 2008; Hannan et al., 2006; Li et al., 2005). Since *nf1* mutant larvae also show increased Ras activity (Shin et al., 2012), we asked whether acute pharmacological inhibition of the Ras effectors MAPK and PI3K could improve memory recall in *nf1* mutants. Small molecules readily cross the developing blood-brain barrier of larval zebrafish until at least 8 days of age (Fleming et al., 2013), facilitating pharmacogenetic approaches for identifying signaling pathways that underlie biological processes and screening of potential therapeutics for neuropsychiatric disorders such as NF1. We treated wild-type, *nf1a*^{+/-}; *nf1b*^{-/-}, and *nf1a*^{-/-}; *nf1b*^{-/-} larvae with inhibitors of MAPK (U0126) or PI3K (wortmannin, BKM120) for 30 min before and throughout training and testing for memory recall. Each compound improved memory recall in *nf1* mutant larvae in a

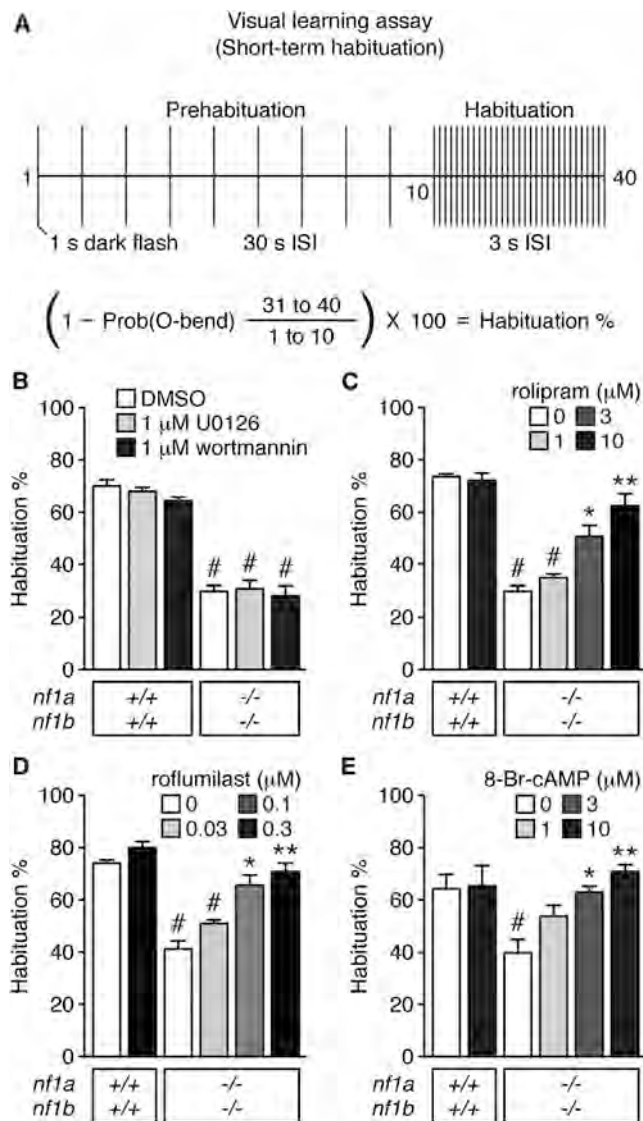


Figure 2. cAMP Signaling Mediates *nf1*-Dependent Visual Learning

(A) Schematic representation of the visual learning assay. (B–E) Mean percentage of habituation to repeated dark-flash stimulation ($n = 3$ groups of 15–20 larvae for all genotype/treatment groups). # $p < 0.001$ versus DMSO-treated wild-type larvae. * $p < 0.01$, ** $p < 0.001$ versus DMSO-treated *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ larvae. One-way ANOVA. Error bars denote SEM. See also Figures S1 and S3.

dose-dependent manner (Figures 1D–1F). Treatment with 1 μM wortmannin restored memory to wild-type levels, and 1 μM U0126 or 3 μM BKM120 yielded significant memory improvement. Although each of these Ras pathway antagonists exhibits known off-target effects, their different selectivity profiles (Bain et al., 2007; Liao and Laufs, 2005; Maira et al., 2012) suggest that nonspecific effects are unlikely to underlie the observed increase in memory recall. Therefore, these results support a conserved function for the neurofibromin GRD domain in regulation of memory formation through the Ras/MAPK/PI3K signaling pathway.

Learning (the acquisition of information) is critical for establishing memory. We evaluated learning by exposing larvae to dark-flash stimuli delivered at 3 s interstimulus intervals (ISIs) and measuring short-term habituation, as indicated by a reduction in the probability of initiating an O-bend response (Figure 2A). *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ larvae showed markedly reduced short-term visual (Figure 2B) and acoustic (Figures S1A and S1B; Shin et al., 2012) habituation compared with wild-type controls. Notably, *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ larvae showed some capacity for learning, which likely accounts for their potential to form memories in the presence of Ras pathway inhibitors (Figures 1D–1F). Larvae with at least one wild-type allele of either *nf1a* or *nf1b* did not show a learning deficit, despite dramatic memory deficits (Figure 1C; M.A.W. and E.D.d.G., unpublished data; Shin et al., 2012). It is possible that our nonassociative habituation assay lacks the necessary sensitivity to detect relatively subtle learning deficiencies in larvae with these genotypes. Attenuating Ras signaling by acute pharmacological inhibition of MAPK (U0126) or PI3K (wortmannin) failed to improve the learning deficit of *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ larvae (Figures 2B and S1B), suggesting that a distinct pathway mediates NF1-dependent learning.

Whole larval lysates revealed reduced cAMP levels in *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ mutants compared with wild-type controls (*nf1a* $^{-/-}$; *nf1b* $^{-/-}$: 33 fmol \pm SEM 2.3 versus wild-type: 79 fmol \pm SEM 7.8, $p < 0.001$). To determine whether reduced cAMP signaling contributed to the learning deficits in *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ mutants, we tested whether enhancing cAMP signaling by acute pharmacological inhibition of phosphodiesterase 4 (PDE4) or stimulation of PKA could improve learning. Inhibition of PDE4 by rolipram or roflumilast, or PKA stimulation by 8-Br-cAMP improved learning behavior in *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ mutants in response to both repetitive visual (Figures 2C–2E) and acoustic (Figures S1C and S1D) stimuli. Treatment with at least 10 μM rolipram, 0.1 μM roflumilast, or 3 μM 8-Br-cAMP improved habituation to wild-type levels. These results provide evidence that cAMP signaling regulates NF1-dependent learning in a vertebrate system.

We next asked whether cAMP signaling regulates NF1-dependent memory in addition to learning. We tested *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ larvae, which show reduced learning and a failure to recall memory, and *nf1a* $^{+/-}$; *nf1b* $^{-/-}$ larvae, which learn normally but fail to form memory, and compared them with wild-type controls. Treatment with 10 μM 8-Br-cAMP, a sufficient dose to restore learning in *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ larvae (Figures 2E and S1D), failed to improve memory recall in either *nf1a* $^{+/-}$; *nf1b* $^{-/-}$ or *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ larvae (Figure S2). These results suggest that cAMP signaling regulates NF1-dependent learning but not memory. Moreover, these results indicate that the memory defects in *nf1a* $^{-/-}$; *nf1b* $^{-/-}$ mutants are not simply attributable to their learning deficit. These data strongly imply that molecularly distinct pathways that control learning and memory are affected in NF1.

Learned behavior requires consolidation to form stable memory. Despite consensus that defective neurofibromin function can result in learning and memory impairments, whether impaired consolidation contributes to memory deficits remains unclear. *nf1a* $^{+/-}$; *nf1b* $^{-/-}$ larvae learn normally (M.A.W. and E.D.d.G., unpublished data; Shin et al., 2012) but show reduced memory recall (Figure 1C). Therefore, we asked whether reduced

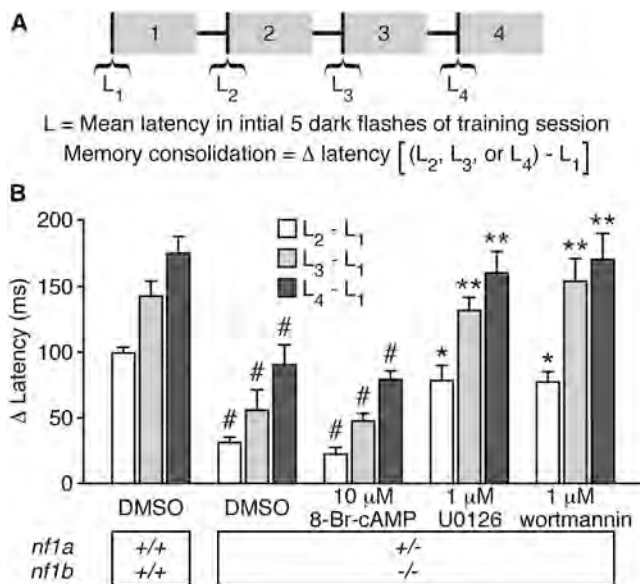


Figure 3. Inhibition of Ras Signaling Improves Memory Consolidation Deficits in *nf1* Mutants

(A) Schematic representation of visual memory consolidation measurement. (B) Mean O-bend latency change comparing responses to dark-flash stimuli 1–5 of sessions 2–4 versus stimuli 1–5 of session 1 ($n = 30$ –139 O-bend maneuvers per genotype/treatment). # $p < 0.001$ versus DMSO-treated wild-type larvae. * $p < 0.01$, ** $p < 0.001$ versus DMSO-treated *nf1a*^{+/-}; *nf1b*^{-/-} larvae. One-way ANOVA. Error bars denote SEM.

See also Figure S3.

memory was due to a consolidation deficit. We determined memory consolidation by calculating the difference between the mean O-bend latency in response to the first five dark-flash stimuli of training session 1 and subsequent training sessions (Figure 3A). Long ISIs between training sessions promote memory consolidation, and therefore spaced training paradigms elicit more stable memory than do massed training paradigms (Beck and Rankin, 1997; Ebbinghaus, 1885). After each session, *nf1a*^{+/-}; *nf1b*^{-/-} larvae showed reduced consolidation compared with wild-type larvae (Figure 3B), suggesting that the memory-recall deficit observed in *nf1a*^{+/-}; *nf1b*^{-/-} larvae (Figure 1C) may be due to a defect in memory consolidation.

To determine the contribution of cAMP and Ras signaling to NF1-dependent memory consolidation, we attempted to improve consolidation in *nf1a*^{+/-}; *nf1b*^{-/-} larvae by pharmacologically enhancing cAMP or attenuating Ras. Enhancing cAMP in *nf1a*^{+/-}; *nf1b*^{-/-} larvae by treatment with 10 μ M 8-Br-cAMP did not increase consolidation (Figure 3B). Pharmacological inhibition of MAPK (1 μ M U0126) or PI3K (1 μ M wortmannin) improved memory consolidation in *nf1a*^{+/-}; *nf1b*^{-/-} larvae to levels indistinguishable from those observed in DMSO-treated wild-type larvae (Figure 3B). These results reveal that deficits in memory consolidation contribute to the etiology of memory dysfunction in NF1 and support a specific role for Ras signaling in mediating NF1-dependent memory formation.

Larvae deficient for *nf1* exhibit learning and memory deficits with characteristics reminiscent of those seen in human NF1

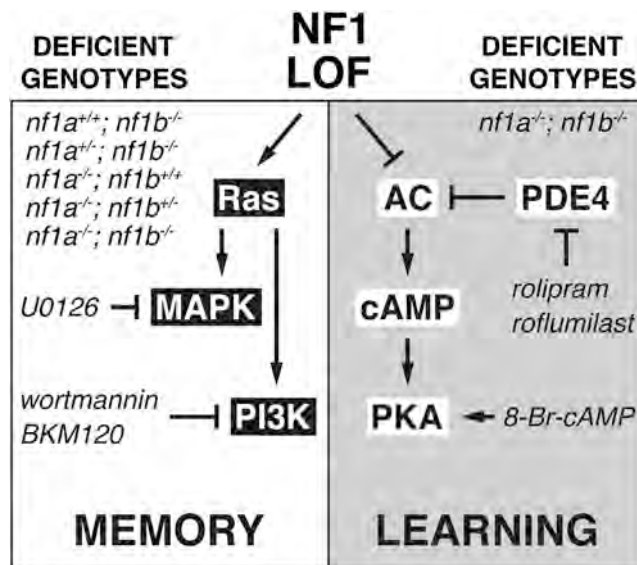


Figure 4. Effects of NF1 Loss of Function on the Ras and cAMP Pathways

The genotypes of the zebrafish *nf1* larvae that exhibited significant memory or learning deficits are shown. The pharmacological agents (italicized) that were used to improve memory or learning in these genotypes, as well as the molecular targets of the agents, are indicated. LOF, loss of function.

patients. We obtained strong evidence in a vertebrate system that NF1 affects at least two distinct signaling pathways that independently modulate learning and memory (Figure 4). A detailed understanding of the structure-function relationship among NF1 mutations, Ras and cAMP signaling, and phenotypes will allow for tailored and personalized therapies for cognitive defects in affected patients. It will also be interesting to determine whether the dynamic regulation of Ras or cAMP signaling in distinct areas of the brain correlates with unique behavioral outcomes. The fact that we observed robust improvements in learning and memory in our experiments even though we used only short-term treatments is encouraging for potential clinical application, and suggests that cognitive defects in this model are not developmental or irreversible. It will be exciting to determine whether these models can be validated in higher vertebrates and whether combination therapy with Ras and cAMP pathway effectors can improve the condition of some NF1 patients.

EXPERIMENTAL PROCEDURES

Generation and Maintenance of Zebrafish

The zebrafish (*Danio rerio*) larvae used in this study were generated from crosses of adults carrying the *nf1a*⁴⁵ and *nf1b*¹⁰ mutant alleles (Shin et al., 2012). Embryos were raised at 28°C in a 14 hr/10 hr light/dark cycle as previously described (Burgess and Granato, 2007a) and all behavioral experiments were conducted with 5 days postfertilization (dpf) larvae. For visual behavioral experiments, larvae were PCR genotyped by clipping a small region of the caudal fin at 3 dpf and genotyping as described previously (Shin et al., 2012). Larvae tested for acoustic habituation were tested individually in a 4 \times 4 grid and genotyped after testing. All animal protocols were approved by the University of Pennsylvania Institutional Animal Care and Use Committee.

Behavioral Assays and Analysis

Dark-flash-induced O-bend responses were elicited, recorded, and measured as previously described (Burgess and Granato, 2007a; Wolman et al., 2011). Larvae were trained and tested at a density of 15 larvae per 9 ml E3 in 6 cm Petri dishes and kept in the dishes during training or testing. To elicit memory formation, larvae were exposed to a training paradigm comprised of four 30 min training sessions, each consisting of exposure to a 1 s dark flash delivered every 15 s. Training sessions were separated by 10 min ISIs. After the fourth session and a 1 hr ISI, larvae were exposed to ten dark flashes with 1 min ISIs to evaluate memory recall. To calculate memory recall, the average latency to initiate an O-bend in untrained larvae was subtracted from the latency to initiate an O-bend in trained larvae. Memory consolidation was calculated by subtracting the average latency to initiate an O-bend in response to dark-flash stimuli 1–5 of training session 1 from the latency to initiate an O-bend in response to dark flashes 1–5 of sessions 2–4.

To measure visual short-term habituation, a series of 40 1 s dark flashes were delivered. Stimuli 1–10 were delivered with 30 s ISIs and stimuli 11–40 were delivered with 3 s ISIs. The percentage of habituation was calculated by dividing the mean O-bend responsiveness to stimuli 31–40 by the mean O-bend responsiveness to stimuli 1–10, subtracting this value from 1, and multiplying by 100. An acoustic short-term habituation assay was performed as previously described (Wolman et al., 2011).

Pharmacology

All compounds were added to the larval media 30 min before and throughout the training and testing paradigm. Cycloheximide (C4859; Sigma-Aldrich), U0126 (9903, Cell Signaling Technology), wortmannin (9951; Cell Signaling Technology), BKM120 (S2247; Selleck Chemicals), rolipram (R6520; Sigma-Aldrich), roflumilast (S2131, Selleck Chemicals), and 8-Br-cAMP (B007; BIOLOG Life Science Institute) were dissolved in 100% DMSO and administered in a final concentration of 1% DMSO. Doses of each compound were prescreened for potential effects on baseline O-bend responsiveness to visual stimuli and short-latency C-bend responsiveness to acoustic stimuli. The defined, stereotyped kinematic parameters of both larval maneuvers were also examined (Burgess and Granato, 2007a, 2007b). Selected doses did not change baseline behavior responsiveness or kinematic performance after 30 min or 4 hr of incubation. Immunohistochemistry with anti-phospho-ERK (4377; Cell Signaling Technology) and anti-phospho-(Ser/Thr) PKA substrate (9621; Cell Signaling Technology) was performed on paraffin-embedded larval tissue after fixation in 4% paraformaldehyde, dehydration, and sectioning at 8 μ M thickness in order to demonstrate the pathway specificity of the pharmacologic inhibitors (Figure S3).

SUPPLEMENTAL INFORMATION

Supplemental Information includes three figures and one movie and can be found with this article online at <http://dx.doi.org/10.1016/j.celrep.2014.07.054>.

AUTHOR CONTRIBUTIONS

E.D.d.G. and M.A.W. designed and performed experiments together and wrote the manuscript. M.G. and J.A.E. designed experiments, supervised the work, and edited the manuscript. S.M.M. and T.A.J. contributed reagents and advice on the experimental design and approach.

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