Finding the most appropriate mouse model of juvenile CLN3 (Batten) disease for therapeutic studies: the importance of genetic background and gender

Attila D. Kovács1 and David A. Pearce1,2,*

ABSTRACT

Mutations in the CLN3 gene cause a fatal neurodegenerative disorder: juvenile CLN3 disease, also known as juvenile Batten disease. The two most commonly utilized mouse models of juvenile CLN3 disease are Cln3-knockout (Cln3−/−) and Cln3 Δex7/8-knock-in mice, the latter mimicking the most frequent disease-causing human mutation. To determine which mouse model has the most pronounced neurological phenotypes that can be used as outcome measures for therapeutic studies, we compared the exploratory activity, motor function and depressive-like behavior of 1-, 3- and 6-month-old Cln3−/− and Cln3 Δex7/8-knock-in mice on two different genetic backgrounds (129S6/SvEv and C57BL/6J). Although, in many cases, the behavior of Cln3−/− and Cln3 Δex7/8 mice was similar, we found genetic-background-, gender- and age-dependent differences between the two mouse models. We also observed large differences in the behavior of the 129S6/SvEv and C57BL/6J wild-type strains, which highlights the strong influence that genetic background can have on phenotype. Based on our results, Cln3−/− male mice on the 129S6/SvEv genetic background are the most appropriate candidates for therapeutic studies. They exhibit motor deficits at 1 and 6 months of age in the vertical pole test, and they were the only mice to show impaired motor coordination in the rotarod test at both 3 and 6 months. Cln3−/− males on the C57BL/6J background and Cln3 Δex7/8 males on the 129S6/SvEv background also provide good outcome measures for therapeutic interventions. Cln3−/− (C57BL/6J) males had serious difficulties in climbing down (at 1 and 6 months) and turning downward on (at 1, 3 and 6 months) the vertical pole, whereas Cln3 Δex7/8 (129S6/SvEv) males climbed down the vertical pole drastically slower than wild-type males at 3 and 6 months of age. Our study demonstrates the importance of testing mouse models on different genetic backgrounds and comparing males and females in order to find the most appropriate disease model for therapeutic studies.

KEY WORDS: Juvenile neuronal ceroid lipofuscinosis, Batten disease, CLN3, Cln3−/− mouse model, Cln3 Δex7/8-knock-in mouse model, 129S6/SvEv, C57BL/6J

INTRODUCTION

Neuronal ceroid lipofuscinoses, also known as Batten disease, are a group of recessively inherited, fatal lysosomal storage disorders characterized by progressive neurodegeneration and the intracellular accumulation of autofluorescent lipopigment (Goebel and Wisniewski, 2004). Batten disease is a rare disease and mostly affects children. Based primarily on the age of onset, Batten disease is classified into six clinical forms: congenital, infantile, late infantile, juvenile, Northern epilepsy and adult (Kufs disease) (Schulz et al., 2013). Vision loss, seizures, and progressive cognitive and motor decline are the common symptoms, and the neurodegeneration ultimately leads to early death. The different forms of Batten disease are currently associated with mutations in 14 genes (Warrier et al., 2013).

Mutations of the CLN3 gene cause the majority of the prevalent, juvenile-onset, form of Batten disease, and this disorder is now called juvenile CLN3 disease to clearly identify the genetic cause and clinical form (International Batten Disease Consortium, 1995; Williams and Mole, 2012). The disease begins between 4 and 10 years of age, and reaches its terminal stage in the late teens or early 20s. CLN3 encodes a putative lysosomal/endosomal transmembrane protein, but the exact function of CLN3 and why CLN3 mutations cause selective neurodegeneration are still unknown. No specific treatment is currently available that could halt or slow the progression of the disease.

The two most commonly utilized mouse models of juvenile CLN3 disease are Cln3-knockout (Cln3−/−) and Cln3 Δex7/8-knock-in mice. The Cln3 Δex7/8 model was generated by targeted recombination to remove exons 7 and 8 from the endogenous Cln3 gene. This created a ‘knock-in’ of exon 7/8-deleted Cln3, to mimic the most frequent disease-causing human mutation (Catman et al., 2002). The Cln3−/− model was created by replacing the start codon and the first six exons with a neo cassette (Mitchison et al., 1999); Cln3−/− mice on the 129S6/SvEv genetic background have been extensively studied (Chan et al., 2009; Kovács and Pearce, 2008; Kovács et al., 2012; Kovács et al., 2011; Kovács et al., 2006; Osório et al., 2009; Pears et al., 2005; Pontikis et al., 2004; Seelafer et al., 2011; Seigel et al., 2002; Weimer et al., 2007; Weimer et al., 2009; Weimer et al., 2006). The Cln3 Δex7/8-knock-in mouse model was generated and initially characterized on a mixed 129S6/SvEv X C57BL/6J genetic background (Catman et al., 2002; Pontikis et al., 2005). In subsequent studies, Cln3 Δex7/8 mice inbred either on the C57BL/6J or C57BL/6N genetic background were used (Finn et al., 2011; Osório et al., 2009; Staropoli et al., 2012). Both Cln3−/− and Cln3 Δex7/8 mice showed characteristic features of the human disease, including intracellular accumulation of autofluorescent storage material (Catman et al., 2002; Mitchison et al., 1999), astrocytosis and microglial activation (Catman et al., 2002; Pontikis et al., 2004; Pontikis et al., 2005; Weimer et al., 2009), neuronal loss (Pontikis...
TRANSLATIONAL IMPACT

Clinical issue
Batten disease, also known as neuronal ceroid lipofuscinoses, is a group of rare fatal lysosomal storage disorders characterized by progressive neuronal degeneration. The disease mostly affects children. Mutations of the CLN3 gene cause the majority of the most prevalent, juvenile-onset, form of the disease, which presents between 4 and 10 years of age and reaches its terminal stage in the late teens or early 20s. No specific treatment is currently available to halt or slow disease progression. To study the pathomechanisms of juvenile Batten disease and develop therapeutic approaches, various mouse models have been developed. It has not been determined, however, which mouse model on which genetic background is the most suitable for therapeutic studies.

Results
The two most commonly utilized mouse models of juvenile Batten disease are Cln3-knockout (Cln3−/−) and Cln3Δex7/8-knock-in mice, the latter mimicking the most frequent disease-causing human mutation. The two mouse models, however, are on different genetic backgrounds. To determine which mouse model on which genetic background has the most pronounced neurological phenotypes that can be used as outcome measures for therapeutic studies, the authors compared the exploratory activity, motor function and depressive-like behavior of 1-, 3- and 6-month-old Cln3−/− and Cln3Δex7/8-knock-in mice on two different genetic backgrounds (129S6/SvEv and C57BL/6J). The authors found genetic-background-, gender- and age-dependent differences between the two mouse models. Large differences in the behavior of the 129S6/SvEv and C57BL/6J wild-type strains were also observed, highlighting the strong influence that genetic background can have on phenotype. Based on the authors’ results, Cln3−/− male mice on the 129S6/SvEv genetic background are the most appropriate candidates for therapeutic studies. They exhibited motor deficits at 1 and 6 months of age in the vertical pole test, and were the only mice to show impaired motor coordination in the rotarod test at both 3 and 6 months.

Implications and future directions
This study provides the first behavioral comparison of Cln3−/− and Cln3Δex7/8-knock-in mice on identical genetic backgrounds. The differences observed reveal that, unlike as previously thought, Cln3Δex7/8 mice might not be true nulls but express residual truncated CLN3. The study demonstrates the importance of testing mouse models on different genetic backgrounds and comparing males and females in order to find the most appropriate disease model for therapeutic studies. Using the most suitable mouse model of a human disease in preclinical drug testing greatly enhances the chance of advancing to successful clinical trials.

RESULTS

Cln3−/− and Cln3Δex7/8-knock-in mice have genetic-background-, gender- and age-dependent differences in exploratory activity
The exploratory behavior of mice was assessed in the dish test, measuring the time that a mouse stayed in a large Petri dish. It should be noted, however, that activity level and anxiety also affect the outcome of the dish test. In this test, we found a large difference between the two wild-type (WT) strains: whereas most 129S6/SvEv mice, both males and females, stayed in the Petri dish for 6 minutes (the time limit of the test), the majority of C57BL/6J mice left the dish in seconds (Fig. 1, asterisks indicate the statistically significant differences between the two WT strains, comparing males to males, and females to females). Because of this extreme difference, results on the two genetic backgrounds are described separately.

Results on the 129S6/SvEv background
One-month-old Cln3−/− mice, both males and females, spent considerably less time in a large Petri dish than Cln3Δex7/8- or WT mice (Fig. 1, top graph). At the age of 3 or 6 months, however, the exploratory activity of WT, Cln3−/− and Cln3Δex7/8 mice was similar (Fig. 1, middle and bottom graphs).

Results on the C57BL/6J background
At both 1 and 3 months of age there were no differences in the exploratory behavior of Cln3−/− and Cln3Δex7/8 mice (Fig. 1, top and middle graph). Three-month-old Cln3Δex7/8 females, however, showed decreased exploratory activity as compared to C57BL/6J WT females (Fig. 1, middle graph). Similarly, the exploratory activity of 6-month-old Cln3Δex7/8 females was decreased compared to WT, and this time to Cln3−/− females as well (Fig. 1, bottom graph). At the same time, 6-month-old Cln3−/− males showed enhanced exploratory activity in comparison to C57BL/6J WT males (Fig. 1, bottom graph). The difference between 6-month-old Cln3−/− and Cln3Δex7/8 males did not reach statistical significance (Fig. 1, bottom graph).

Genetic-background-, gender- and age-dependent differences in the motor phenotypes of Cln3−/− and Cln3Δex7/8-knock-in mice
After the dish test, the same mice were also tested in a modified vertical pole test. This test measures the balance, spatial orientation and motor coordination, although anxiety or motivation to move can also affect the test results.

Climbing down the vertical pole
First, the ability of mice to climb down a vertical pole was examined (Fig. 2). Whereas WT mice climbed down the pole quickly and touched the base of the pole without hesitation, Cln3−/− and Cln3Δex7/8 mice showed abnormal behavior, which included turning upward, falling off the pole, slowly descending, freezing on the pole and hesitating to touch the base of the pole. Cln3−/− males on both genetic backgrounds climbed down significantly slower than their WT counterparts at 1 and 6 months of age. Whereas Cln3Δex7/8 males on the C57BL/6J background showed the same age-dependent
motor deficit as $Cln3^{-/-}$ males (at 1 and 6 months), $Cln3^{ex7/8}$ males on the 129S6/SvEv background exhibited a marked delay in climbing down at 3 and 6 months as compared to WT males (Fig. 2). The differences between $Cln3^{-/-}$ and $Cln3^{ex7/8}$ males on either genetic background did not reach statistical significance at 1, 3 or 6 months. The climbing-down ability of $Cln3^{-/-}$ and $Cln3^{ex7/8}$ females, however, varied depending on age and genetic background. On the C57BL/6J background, 1- and 3-month-old $Cln3^{-/-}$ females climbed down the pole dramatically slower than $Cln3^{ex7/8}$ or WT females (Fig. 2, top and middle graphs). At 6 months, however, $Cln3^{-/-}$ and $Cln3^{ex7/8}$ females (on C57BL/6J) showed similar motor deficits as compared to WT females (Fig. 2, bottom graph). Although the climbing-down time of $Cln3^{-/-}$ and $Cln3^{ex7/8}$ females on the 129S6/SvEv background was not statistically different at 1, 3 or 6 months, $Cln3^{-/-}$ and $Cln3^{ex7/8}$ females showed age-dependent differences in comparison to WT females. $Cln3^{-/-}$ (129S6/SvEv) females showed motor deficits at 1 and 3 months, whereas $Cln3^{ex7/8}$ (129S6/SvEv) females climbed down significantly slower than 129S6/SvEv WT females at 3 and 6 months (Fig. 2). The two WT strains performed similarly in the climbing-down test, with the only exception that, at 6 months of age, 129S6/SvEv females reached the bases of the pole significantly later than C57BL/6J females (Fig. 2, bottom graph).

Turning downward on the vertical pole

The ability of mice to turn downward on a vertical pole was also tested. There was a huge difference between 129S6/SvEv and C57BL/6J WT mice: the majority of 129S6/SvEv mice (both males and females) did not turn downward at all during the test trials (Fig. 3). On the 129S6/SvEv background, only 1-month-old $Cln3^{-/-}$...
and Cln3Δex7/8 females exhibited a phenotype: a statistically significant delay in turning downward as compared to WT females (Fig. 3, top graph).

On the C57BL/6J background, Cln3−/− males at all three ages turned downward substantially later than WT males, whereas Cln3Δex7/8 males were only different from WT males at 1 month of age (Fig. 3). The turning-downward performance of 1-month-old Cln3Δex7/8 males, however, was significantly worse than that of 1-month-old Cln3−/− males (Fig. 3, top graph). Cln3−/− females on the C57BL/6J background had an impaired ability to turn downward at 3 months of age as compared to their WT or Cln3Δex7/8 counterparts (Fig. 3, middle graph). In contrast, at 6 months, Cln3Δex7/8 females (on C57BL/6J) showed a considerable delay in turning downward, whereas Cln3−/− females (on C57BL/6J) performed like WTs (Fig. 3, bottom graph).

Rotarod test
The rotarod test assesses balance and motor coordination, although motor learning capability and endurance level can also affect the rotarod performance. The sensitivity of the rotarod test depends on the task parameters, particularly on the acceleration (Carter et al., 1999; Pallier et al., 2009; Rustay et al., 2003). After trying different
rotarod protocols and accelerations in a previous study (Kovács and Pearce, 2013), we found that a 0.2 rpm/s acceleration is the most suitable to detect even slight differences in rotarod performance. At 3 and 6 months of age, 1 day after the dish test, vertical pole test and tail suspension test, the same mice were also tested in an accelerating rotarod test (0.2 rpm/s starting from 0 rpm). Cln3Δex7/8, but not Cln3Δex7/8-KI, males on the 129S6/SvEv background fell from the rotating rod significantly sooner than WT males. Columns and bars represent mean±s.e.m. (n=10-12). The same mice were tested at 3 and 6 months of age. Statistical significance was determined by 1-way ANOVA with Bonferroni’s post-test for multiple comparisons. Asterisks indicate significant differences between 129S6/SvEv and C57BL/6J WT mice, males versus males, and females versus females: *P<0.05, **P<0.01 and ****P<0.0001.

extraordinary rotarod performance of Cln3Δex7/8 females is that the Cln3Δex7/8-derived truncated CLN3 increased the motivation of staying on the rotating rod and/or the endurance specifically in females.

We also compared the rotarod performance of the two WT strains and found that 3-month-old 129S6/SvEv males and females, and 6-month-old 129S6/SvEv females, fell from the rotating rod significantly sooner than their C57BL/6J counterparts (Fig. 4).

Genetic-background-, gender- and age-specific differences in the depressive-like behavior of Cln3Δex7/8 and Cln3Δex7/8-KI knock-in mice

The tail suspension test was used to assess the depressive-like behavior of mice. The duration of immobility was measured in 1-minute bins for 6 minutes. Fig. 5 shows the total times of immobility (in 6 minutes). At 1 month of age, Cln3Δex7/8 (129S6/SvEv) females behaved more depressively, staying immobilized significantly longer than Cln3Δex7/8 (129S6/SvEv) or WT females (Fig. 5, top graph). This difference in total immobilization time could not be detected at 3 or 6 months (Fig. 5, middle and bottom graphs). The time course plot revealed significantly increased immobility of Cln3Δex7/8 (129S6/SvEv) females in the 4th-6th minutes at 1 month (Fig. 6A) and in the 4th minute at 3 months (Fig. 6B).

At 3 months of age, Cln3Δex7/8 (C57BL/6J) males showed abnormally increased depression and spent markedly less time immobilized than C57BL/6J males (Fig. 5, middle graph). At 6 months of age, Cln3Δex7/8 (129S6/SvEv) males spent significantly less time immobilized than Cln3Δex7/8 (129S6/SvEv) or WT males (Fig. 5, bottom graph). Furthermore, 6-month-old Cln3Δex7/8 (129S6/SvEv) females, Cln3Δex7/8 (C57BL/6J) males and especially Cln3Δex7/8 (C57BL/6J) males exhibited abnormally increased depression and stayed immobilized for a shorter time than their WT counterparts (Fig. 5, bottom graph; Fig. 6C). The time course plot revealed a statistically significant difference between Cln3Δex7/8 (C57BL/6J) and Cln3Δex7/8 (C57BL/6J) males in the 5th minute (Fig. 6C).

We also compared the depressive-like behavior of the two WT strains and found that 1- and 3-month-old C57BL/6J males and females, and 6-month-old C57BL/6J males stayed immobilized substantially longer than their 129S6/SvEv counterparts (Fig. 5; Fig. 6D-F).

All the other time courses of immobility not presented in Fig. 6 are shown in supplementary material Figs S1-S3.

Genetic-background-, gender- and age-specific differences in the weight of Cln3Δex7/8 and Cln3Δex7/8-KI knock-in mice

For weight comparison, mice were weighed 30-40 minutes before starting the behavioral tests with them. The same mice were weighed at 1, 3 and 6 months of age. On the C57BL/6J genetic background, no weight differences were found between Cln3Δex7/8 and Cln3Δex7/8 mice or between WT and mutant mice at any age (Fig. 7). On the 129S6/SvEv background, 1-month-old Cln3Δex7/8 mice, both males and females, were strikingly heavier than Cln3Δex7/8 mice (Fig. 7, top graph). One-month-old Cln3Δex7/8 (129S6/SvEv) females were also markedly heavier than WT 129S6/SvEv females. At the same time, 1-month-old Cln3Δex7/8 (129S6/SvEv) females were significantly lighter than 129S6/SvEv females (Fig. 7, top graph). At 3 months of age, Cln3Δex7/8 (129S6/SvEv) females were considerably heavier than Cln3Δex7/8 (129S6/SvEv) females (Fig. 7, middle graph). Because the observed weight differences might affect the performance in behavioral tests, particularly in motor skill tests, we carried out correlation analyses between the weight and the
behavioral test results. The weight of 1- and 3-month-old 129S6/SvEv, Cln3−/− (129S6/SvEv) and Cln3Δex7/8 (129S6/SvEv) mice did not correlate with their performance in any of the behavioral tests, indicating that, in our study, the weight differences did not influence the behavioral test results.

We also compared the weights in the two WT strains and found that 129S6/SvEv males were significantly lighter than C57BL/6J males at 3 and 6 months (Fig. 7, middle and bottom graph). Moreover, independently of the genotype and age, males were always substantially heavier than females and the gender-specific weight difference increased with age (supplementary material Fig. S4).

**DISCUSSION**

Mouse models of juvenile CLN3 disease: suitability for therapeutic studies

In the present study, we compared the exploratory activity, motor function and depressive-like behavior of Cln3−/− and Cln3Δex7/8-knock-in mice on two different genetic backgrounds (129S6/SvEv and C57BL/6J) to determine which mouse model on which genetic background has the most pronounced neurological phenotypes that can be used as outcome measures for therapeutic studies. Based on our results, Cln3−/− male mice on the 129S6/SvEv genetic background are the most appropriate candidates for therapeutic studies. They show motor deficits at 1 and 6 months of age in the vertical pole test (Fig. 2), and they were the only mice exhibiting impaired motor coordination in the rotarod test at both 3 and 6 months (Fig. 4). Cln3−/− males on the C57BL/6J background and Cln3Δex7/8 males on the 129S6/SvEv background also provide good outcome measures for therapeutic interventions. Cln3−/− (C57BL/6J) males had serious difficulties in climbing down (at 1 and 6 months) and turning downward on (at 1, 3 and 6 months) the vertical pole (Figs 2-3), whereas Cln3Δex7/8 (129S6/SvEv) males climbed down the vertical pole drastically slower than WT males at 3 and 6 months of age (Fig. 2). It should be noted that various other behavioral tests (e.g. cognitive tests, open field, light-dark box, gait analysis, variations of rotarod) not used in our study could provide additional valuable readouts for one or more of the models. Similarly, other genetic backgrounds might prove superior in resolving CLN3-deficient behavioral phenotypes.

Our current selection of the most appropriate mouse models was based solely on behavioral tests. Because mouse models of juvenile CLN3 disease show age-dependent neuropathological changes, including microglial activation, astrocytosis and localized neuronal loss (Catton et al., 2002; Pontikis et al., 2004; Pontikis et al., 2005; Weimer et al., 2009), brain pathology is another important (but terminal) outcome measure for therapeutic studies. Further studies will determine whether the neurological deficits in our chosen models correlate with the severity and progression of neuropathological changes.

**Similarities and differences in the neurological phenotypes of Cln3−/− and Cln3Δex7/8-knock-in mice**

The mouse Cln3Δex7/8 gene mimics the most frequent disease-causing human mutation (Catton et al., 2002). The mutant Cln3Δex7/8 (mouse) and CLN3Δex7/8 (human) genes theoretically produce a truncated protein, which might have a residual function (Kitzmüller et al., 2008). Evidence suggests, however, that cellular quality-control mechanisms at the RNA and protein levels degrade the mutant human and mouse transcript and polypeptide (Chan et al., 2008), and, thus, both CLN3Δex7/8 (human) and Cln3Δex7/8 (mouse) are likely null mutations. If Cln3Δex7/8 is indeed a null mutation then the behavioral phenotypes and their progression in the Cln3−/− and Cln3Δex7/8-knock-in mouse models of juvenile Batten disease should be very similar. Our results show that, although in many cases the behavior of Cln3−/− and Cln3Δex7/8 mice was similar, genetic-background-, gender- and age-dependent differences existed between the two mouse models, Cln3−/− mice showing more severe phenotypes in some cases whereas Cln3Δex7/8 mice exhibited more pronounced behavioral deficits in other instances. This could suggest that, in Cln3Δex7/8 mice, a truncated Cln3 transcript has enough expression to impart a residual but presumably partially functional Cln3 gene product. In a few instances, however, the behavioral defect was more severe or only exhibited in Cln3Δex7/8 mice, indicating a detrimental effect of truncated CLN3 in...
comparison to the complete lack of CLN3 in Cln3\(^{-/-}\) mice. The slight differences in the genetic background between our Cln3\(^{-/-}\) and Cln3\(^{-/-}\)Δex7/8 mice (see Materials and Methods) might also contribute to the observed behavioral differences.

Recent studies in the Cln3\(^{-/-}\) and Cln3\(^{-/-}\)Δex7/8 mouse models indicate that juvenile Batten disease has a neurodevelopmental component resulting in early disease phenotypes (at \(\leq 1\) month of age) in these mice (Osório et al., 2009; Weimer et al., 2009). Some of these early neurological problems, however, might be reduced or eliminated by compensatory mechanisms during later brain development and maturation [see e.g. Cln3\(^{-/-}\) (129S6/SvEv) males and females in the dish test (Fig. 1); Cln3\(^{-/-}\) (129S6/SvEv) females, Cln3\(^{-/-}\) (C57BL/6J) males and Cln3\(^{-/-}\)Δex7/8 (C57BL/6J) males in the climb-down test (Fig. 2); Cln3\(^{-/-}\) (129S6/SvEv) females, Cln3\(^{-/-}\)Δex7/8 (129S6/SvEv) females and Cln3\(^{-/-}\)Δex7/8 (C57BL/6J) males in the turn-downward test (Fig. 3); and Cln3\(^{-/-}\)Δex7/8 (129S6/SvEv) females in the tail suspension test (Fig. 5)]. Nevertheless, progressive neurological deficits, depending on the genetic background and the disease model, are also evident [see e.g. Cln3\(^{-/-}\)Δex7/8 (129S6/SvEv) males in the climb-down test (Fig. 2); Cln3\(^{-/-}\) (129S6/SvEv) males, Cln3\(^{-/-}\)Δex7/8 (129S6/SvEv) females and Cln3\(^{-/-}\)Δex7/8 (C57BL/6J) males in the tail suspension test (Fig. 5)].

Our results also indicate that the vertical pole test is the most representative to detect the motor phenotype of juvenile Batten disease. This was the only test that showed deficits for both Cln3\(^{-/-}\)
and $Cln3^{Δex7/8}$ models on both genetic backgrounds and for both sexes, at least at one age. Furthermore, because WT C57BL/6J mice (in contrast to 129S6/SvEv mice) effectively turned downward on the vertical pole and both $Cln3^{−/−}$ and $Cln3^{Δex7/8}$ mice on the C57BL/6J background showed impaired ability of turning downward, the standard vertical pole test that takes the sum of turn-downward and climb-down time would reveal a stronger motor phenotype for the C57BL/6J background.

**Choice of the genetic background for mouse models of neurodegenerative and neurological diseases**

We observed large differences in the behavior of the 129S6/SvEv and C57BL/6J WT strains (Figs 1, 3-5). Our findings in the rotarod test (better performance of C57BL/6J than 129S6/SvEv mice) and in the tail suspension test (dramatically longer immobility of C57BL/6J than 129S6/SvEv mice) are in agreement with previous reports (Cook et al., 2002; Kelly et al., 1998; Miller et al., 2010). Substantial differences in the locomotor activity, stress reactivity and anxiety-related behaviors of 129S6/SvEv and C57BL/6J mice have also been demonstrated (Cook et al., 2002; Paulus et al., 1999; Van Bogaert et al., 2006). The large behavioral differences between the two WT strains highlight the strong influence that genetic background can have on the disease phenotypes of transgenic mice. In our study, for example, $Cln3^{Δex7/8}$-knock-in mice only on the 129S6/SvEv background had motor deficits at 3 months of age (Fig. 2). The genetic background, as several studies have shown, can modify, and even suppress, the effect of a transgene or gene deletion (Bilovoyk, et al., 2003; Duyse and Lockridge, 2006; Kelly et al., 1998; Lariviere et al., 2001; Lloret et al., 2006; Magara et al., 1999; Mahajan et al., 2004; Nguyen et al., 1997; Tang et al., 2003; Yang et al., 2005).

Although C57BL/6J embryonic stem cell lines became available in recent years, most transgenic mice had been generated using 129S6/SvEv embryonic stem cells. Because 129S6/SvEv mice have a neuroanatomical defect (hypoplasia of the corpus callosum in 60-80% of the mice) (Balogh et al., 1999), carry the Disrupted-in-Schizophrenia 1 (DISC1) mutation (Kim et al., 2012; Koike et al., 2006), and do not perform well in learning tests (Balogh et al., 1999), a common practice has been to backcross 129S6/SvEv transgenic mice to the C57BL/6J genetic background. The C57BL/6J background, however, also has disadvantages. As compared to 129S6/SvEv mice, C57BL/6J mice are hyperactive and aggressive, probably partly due to the fact that the cell surface expression of AMPA (α-amino-3-hydroxy-5-methyl-4-isoxazolepropionate)- and NMDA (N-methyl-D-aspartate)-type glutamate receptors are markedly higher in the brain of C57BL/6J mice (Finn et al., 2010). Furthermore, C57BL/6J mice have a relatively low bone density (Sheng et al., 1999), develop age-related hearing loss (Johnson et al., 1997), and are also susceptible to diet-induced obesity (Collins et al., 2004), type 2 diabetes (Freeman et al., 2006; Parekh et al., 1998) and atherosclerosis (Nishina et al., 1990; Paigen et al., 1985). Because glutamate receptor function is induced obesity (Collins et al., 2004), type 2 diabetes (Freeman et al., 2006; Parekh et al., 1998) and atherosclerosis (Nishina et al., 1990; Paigen et al., 1985). Because glutamate receptor function is enhanced in C57BL/6J neurons as compared to 129S6/SvEv neurons (Finn et al., 2010), the 129S6/SvEv background seems to be more appropriate for studying neurodegenerative diseases where enhanced glutamate receptor function might be involved in the pathophysiology.

The variable neuroanatomical defect of hypoplastic corpus callosum in 60-80% of 129S6/SvEv mice (Balogh et al., 1999) could have a significant effect in behavioral tests. If this is the case, variation in the test results should be higher on the 129S6/SvEv background (intact corpus callosum in 20-40% of the mice) than on the C57BL/6J background (intact corpus callosum in all mice). In our vertical pole test, rotarod test and tail suspension test, however, as the error bars in Figs 2-5 show, the test result variations on the two genetic backgrounds were very similar.

In summary, our study demonstrates the importance of testing mouse models on different genetic backgrounds and comparing males and females in order to find the most appropriate disease model for therapeutic studies. In addition, we provide the first behavioral comparison of $Cln3^{−/−}$ and $Cln3^{Δex7/8}$-knock-in mice on identical genetic backgrounds, revealing that the $Cln3^{Δex7/8}$ mice might differ from $Cln3^{−/−}$ mice due to residually expressed truncated CLN3.

**MATERIALS AND METHODS**

**Animals**

We maintained $Cln3^{−/−}$ mice on the 129S6/SvEv genetic background ($Cln3^{−/−}$ mice were originally backcrossed with 129S6/SvEv mice for 12
generations), and Cln3<sup>Δex7/8</sup>-knock-in mice on the C57BL/6J genetic background (Cln3<sup>Δex7/8</sup>-knock-in mice were originally backcrossed with C57BL/6J mice for 12 generations). To compare the two mouse models we backcrossed Cln3<sup>−/−</sup> (129S6/SvEv) mice to the C57BL/6J, and Cln3<sup>Δex7/8</sup> (C57BL/6J) mice to the 129S6/SvEv genetic background for ten generations. To further verify the genetic background of the mouse strains used in our study, tail snips of representative mice (two males and two females from each strain) were sent to The Jackson Laboratory (Bar Harbor, Maine) for genome scanning. Analysis of 158 SNPs polymorphic between the C57BL/6 and 129 strains and covering 19 autosomes and the X chromosome with a density of ~15-20 Mb showed that our Cln3<sup>−/−</sup> (129S6/SvEv) and Cln3<sup>Δex7/8</sup> (129S6/SvEv) mice have 99.4% and 97.6% of their genome, respectively, from the 129S6/SvEv strain, and our Cln3<sup>−/−</sup> (C57BL/6J) and Cln3<sup>Δex7/8</sup> (C57BL/6J) mice have 99.4% and 98.1% of their genome, respectively, from the C57BL/6J strain (supplementary material Table S1).

129S6/SvEv and C57BL/6J WT mice maintained in our mouse colony were the controls in the behavioral experiments. Mice were housed in individually ventilated microisolator cages (four or five mice/cage) with <i>ad libitum</i> access to food and water. Mice were fed with the Teklad Global 2918 diet (Harlan Laboratories, Indianapolis, IN), and their drinking water was tap water. All procedures were carried out according to the guidelines of the Animal Welfare Act and NIH policies, and were approved by the Sanford Research Animal Care and Use Committee.

**Behavioral testing**

Mice were transported to the behavioral testing room where the lights had been dimmed. Mice were labeled on their tails for easy identification, weighed, and were allowed to acclimatize to the room for at least 20 minutes before starting the behavioral tests. All mice were tested first in the dish test, then in the modified vertical pole test, and finally in the tail suspension test. One day later (in the case of 3- and 6-month-old mice) the same mice were also tested in the rotarod test. All behavioral tests were carried out under dim light to keep the anxiety level of mice minimal. The same mice were tested at 1, 3 and 6 months of age.

**Dish test**

The dish test measures the exploratory behavior of mice, although activity level and anxiety also affect the outcome of this test. The mouse was placed in a large plastic Petri dish (diameter: 15 cm; height: 1.5 cm) located in the middle of a clean table, and the time until the mouse stepped out of the dish with all four legs was measured in a single trial. The time limit of the trial was 6 minutes. The Petri dish was cleaned between mice from the same cage (same genotype and gender), and a new Petri dish was used for each cage.

**Modified vertical pole test**

With the vertical pole, the balance, spatial orientation and motor coordination of mice are tested. However, anxiety or motivation to move might also affect the test results. In the traditional vertical pole test (see e.g. Iwamoto et al., 2003), the mouse is placed on top of the pole head upward, and the time until it turns downwards and climbs down to the base of the pole is measured. Because the majority of our mice on the 129S6/SvEv genetic background, including WT mice, do not turn downward at all (see Fig. 3), we modified the vertical pole test so it starts with the climb down. The vertical pole was an all-thread metal rod (diameter: 1.27 cm; height: 66 cm), screwed to a 3.81-cm-thick plastic block (24.5 cm x 25.4 cm). The plastic block was covered with a 3.81-cm-thick green hunting seat cushion (nitrile rubber/PVC foam) to prevent the mice from injury if they fell from the pole. The height of the pole measured from the surface of the hunting seat cushion was 59 cm. The mouse was placed, head downward, on top of the pole, and the time until the mouse turned completely downward was measured in four consecutive trials. Each climbing-down and turning-downward trial was terminated after 60 seconds to avoid exhaustion. If the mouse fell from the pole, a trial result of 60 seconds was given. The time to climb down (sum of the five trials in seconds), and the time to turn downward (sum of the four trials in seconds) were calculated for each mouse.

**Tail suspension test**

This test measures the depressive-like behavior of mice (Tanioguchi et al., 2009). Rodents subjected to the short-term, inescapable stress of being suspended by their tail develop an immobile posture. Various antidepressant drugs reverse the immobility and promote the occurrence of escape-related behavior (Cryan et al., 2005). Mice were suspended 45 cm above table level by tying their tails to Tygon tubing tightened to an extension support ring on an iron support stand. The duration of immobility (defined as the absence of all movement except for those required for respiration) was measured in 1-minute bins for 6 minutes.

**Rotarod test**

The rotarod measures the ability of the mouse to maintain balance on a motor-driven, rotating rod. Thus, the fore- and hind-limb motor coordination and balance can be analyzed. Motor learning capability and endurance level might also affect the rotarod performance. The rotarod test using two Rotarod-5 accelerating rotarod instruments (Columbus Instruments, Columbus, OH; diameter of the rotating rod: 3 cm) was performed as described previously (Kovács and Pearce, 2013), with some modifications. The start speed of the rotarod was 0 rpm and the acceleration was set to 0.2 rpm/s. The cut-off time was set at 240 seconds but all mice fell from the rotarod way before the set cut-off time. Mice were trained on the rotarod in three consecutive runs. Following training, mice rested for 1.5 hours and then were tested on the rotarod in three test trials each consisting of three consecutive runs, with 15 minutes of rest between the trials. The average latency to fall from the rotating rod in the test trials (average of the nine runs in the three trials) was calculated for each mouse.

**Statistical analysis**

Statistical analysis was performed using GraphPad Prism 5.04 (GraphPad Software, San Diego, CA). Most of the data sets from the vertical pole test, rotarod test, tail suspension test and weight measurement passed the normality test (alpha level 0.05); therefore, 1-way ANOVA with Bonferroni’s post-test was used for comparison in these behavioral tests and for weight comparison as well. Because most data sets from the dish test did not pass the normality test (alpha level 0.05), the non-parametric Kruskal-Wallis test with Dunn’s post-test was applied for comparison in this case. To compare the time courses in the tail suspension test, repeated measures 2-way ANOVA with Bonferroni’s post-test was used. Alpha level was 0.05 in all statistical tests.

**Acknowledgements**

We thank Sarah Radel, Sarah Brink, Camille Parker and Logan Langin for maintaining our mouse colony.

**Competing interests**

The authors declare no competing or financial interests.

**Author contributions**

A.D.K. and D.A.P. designed the study, A.D.K. performed the experiments, and A.D.K. and D.A.P. analyzed the data and wrote the paper.

**Funding**

This work was supported by the Luke and Rachel Batten Foundation and in part by the National Institutes of Health [NS044310 and TW008433].

**Supplementary material**

Supplementary material available online at http://dmm.biologists.org/lookup/suppl?doi:10.1242/dmm.018804/-/DC1

**References**


collateral defects in transgenic mice for the study of atherosclerosis in the mouse.

Magara, F., Müller, U., Li, Z. W., Lipp, H. P., Weissmann, C., Stagglar, M. and
Wolfer, D. P. (1999). Genetic background changes the pattern of forebrain
commissure defects in transgenic mice underexpressing the beta-amyloid precursor

The nuclear hormone receptor coactivator NURR1 is a pleiotropic modulator affecting
growth, development, apoptosis, reproduction, and wound repair. Mol. Cell. Biol. 24,
661-672.

Phenotypic characterization of a genetically diverse panel of mice for behavioral

deficits in mice transgenic for the human Huntington’s disease mutation.

The Batten Mouse Model Consortium (1999). Targeted disruption of the Ct3
model mouse for Batten disease. The Batten Mouse Model Consortium [corrected].
Biol. Reprod. 61, 231-334.

Nguyen, U., Camenisch, T., Snouwaert, J. N., Hicks, E., Coffman, T. M., Anderson,

deficits in a transgenic mouse model of Huntington’s disease is task-
and protocol-dependent: influence of non-motor factors on locomotor function.

Reversal of diet-induced obesity and diabetes in C57BL/6J mice. Metabolism 47,
1089-1096.

organization is independent of locomotor activity in 129 and C57 mouse strains.
Brain Res. 835, 23-36.

Pears, M. R., Cooper, J. D., Mitchison, H. M., Mortin-Smith, R. J., Pearce, D. A. and
Griffith, J. L. (2005). High resolution 1H NMR-based metabolomics indicates a
neurotransmitter cycling defect in cerebral tissue from a mouse model of
Batten disease. J. Biol. Chem. 280, 42508-42514.

Pontikis, C. C., Cella, C. V., Parhar, N., Lim, M. J., Chakrabarti, S., Mitchison, H. M.,
Moore, M. C., Rezzu, R. and Pears, M. R. (2004). Late onset neurodegeneration in the Ct3
model mouse of juvenile neuronal ceroid lipofuscinosis is preceded by low glial activation.
Brain Res. 1023, 231-242.

Pontikis, C. C., Cotman, S. L., MacDonald, M. E. and Cooper, J. D. (2005).
Thalamocortical neuron loss and localized astrocytosis in the Cln3Deltaex7/8 knock-

rotarod performance and sensitivity to ethanol in mice. Behav. Brain Res. 141,
273-274.


Seerhaer, S. S., Ramirez-Montalegre, D., Wong, A. M., Chan, C. H., Castaneda, J.,
Horak, M., Ahmad, M., Lim, M. J., Cooper, J. D., Pearce, D. A. (2011).
Immunosuppression alters diseases severity in juvenile Batten disease mice.
Neuropharmacology 200, 169-172.

Seigel, G. M., Lotery, A. K., Kummer, A. B., Bernard, D. J., Greene, N. D., Turmaine, M.,
pathology and function in a Ct3 knock out mouse model of juvenile Neuronal Ceroid

Sheng, M., Haylk, D. J., Beamer, W. G., Donahue, L. R., Rosen, C. J., Lau, K. H.
and Wergedal, J. E. (1999). Histomorphometric studies show that bone formation
and bone mineral apposition rates are increased in C57BL/6J (high density) compared to
C57BL/6J (low density) mice during growth. Bone 25, 421-429.

Staropoli, J. F., Haliw, L., Biswas, S., Garrett, L. H., Becker, L., Skosyrski, S.,
Da Silva-Buttus, P., Calzada-Wack, J., Neff, F. et al. (2012). Large-scale
metabolic phenotyping of an accurate genetic model mouse of juvenile NCL: 
Transgenic mice identify novel early pathology outside the central nervous system. 
PLOS ONE 7, e38310.

(2010). Genetic variations in vascular determinants of vascular development of

Taniguchi, S., Nakazawa, T., Tanimura, A., Kiyama, Y., Tezuka, T., Watabe, A. M.,
Involvement of NTRK2 tyrosine phosphorylation in depression-related behaviour. 
EMBO J. 28, 3717-3729.

Van Bogaert, M. J., Groenink, L., Oosting, R. S., Westphal, K. G., van der Gutten,
J. and Olivier, B. (2008). Mouse strain differences in autonomic responses to 
exercise. Genes Brain Behav. 5, 139-149.


