Neurocalcin delta suppression protects against spinal muscular atrophy in humans and across species by restoring impaired endocytosis

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ABSTRACT

Homozygous *SMN1* loss causes spinal muscular atrophy (SMA), the most common lethal genetic childhood motor neuron disease. *SMN1* encodes SMN, a ubiquitous housekeeping protein, which makes the primarily motor neuron-specific phenotype rather unexpected. SMA individuals harbor low SMN expression from one to six *SMN2* copies, which is insufficient to functionally compensate for *SMN1* loss. However, rarely individuals with homozygous absence of *SMN1* and only three to four *SMN2* copies are fully asymptomatic, suggesting protection through genetic modifier(s). Previously, we identified plastin 3 (PLS3) overexpression as an SMA protective modifier in humans and showed that SMN deficit impairs endocytosis, which is rescued by elevated PLS3 levels. Here, we identify reduction of the neuronal calcium sensor Neurocalcin delta (NCALD) as a protective SMA modifier in five asymptomatic *SMN1*-deleted individuals carrying only four *SMN2* copies. We demonstrate that NCALD is a Ca^{2+}-dependent negative regulator of endocytosis, as NCALD knockdown improves endocytosis in SMA models and ameliorates pharmacologically induced endocytosis defects in zebrafish. Importantly, NCALD knockdown effectively ameliorates SMA-associated pathological defects across species, including worm, zebrafish and mouse. In conclusion, our study identifies a previously unknown protective SMA modifier in humans, demonstrates modifier impact in three different SMA animal models and suggests a potential combinatorial therapeutic strategy to efficiently treat SMA. Since both protective modifiers restore endocytosis, our results confirm that endocytosis is a major cellular mechanism perturbed in SMA and emphasize the power of protective modifiers for understanding disease mechanism and developing therapies.

INTRODUCTION

In monogenic disorders, genetic modifiers can influence disease-causing mechanisms resulting in incomplete penetrance[1]. Identification of such modifiers is of utmost relevance since they can uncover regulatory networks and pathological mechanisms, as well as allow identification of therapeutic pathways. For recessive disorders, full protection through modifiers is extremely rare, making their identification highly challenging.

Spinal muscular atrophy (SMA), a motor neuron disease, is one of the most common and devastating autosomal recessive disorders, for which no treatment is available yet. However, various clinical trials using antisense oligonucleotides (ASOs), small molecules or gene therapy show highly promising ameliorations[2]. Most SMA individuals show homozygous absence of exon 7 of the *survival motor neuron 1* (*SMN1*) [MIM: 600354][3], allowing easy and efficient genetic testing[4]. *SMN1* encodes SMN, a housekeeping protein involved in snRNP biogenesis and splicing, microRNA biogenesis, transcription and translation regulation, and others[5-8]; full absence of SMN causes embryonic lethality[9]. Only humans have an almost identical copy, *SMN2* [MIM: 601627], however this produces only ~10% correctly spliced full-length transcript and protein, due to a single silent mutation affecting an exonic splicing enhancer and creating a new splice silencer[10-12]. In SMA individuals, *SMN2* is the only source of SMN, thus its copy number (between 1-6) determines SMA severity[13]. In type 1 SMA (SMA1 [MIM: 253300]), the severe and most common form (60%), the majority of individuals carry two *SMN2* copies and die within the first two years of life. Most type 2 SMA (SMA2 [MIM: 253550]) affected individuals carry three *SMN2* copies and are never able to walk. In type 3 SMA (SMA3 [MIM: 253400]), the mild form, most individuals carry four *SMN2* copies and are able to walk, but often become wheel-chair bound[14].

Despite the important housekeeping function of SMN, reduced levels primarily cause spinal motor neuron (MN) dysfunction in all types of SMA[14]. Thus, MN loss, impaired maturation and maintenance of neuromuscular junctions (NMJs), and decreased proprioceptive inputs on MN soma are hallmarks of SMA[15-17]. Nonetheless, dramatic reduction of SMN below a certain threshold, as seen in severely-affected SMA individuals or animal models, compromise almost

every organ and many different cellular processes, which is in line with the essential function of SMN in all cell types[18; 19]. Therefore, we reasoned that the search for the main cellular pathway specifically driving MN dysfunction has to be carried out in mildly affected SMA individuals, in whom only motor neuron function is impaired and moreover, that protective modifiers identified in these individuals may reveal the critical underlying cellular mechanism.

To do so, we took advantage of very rarely occurring SMA-discordant families, in which relatives of SMA affected individuals carry a homozygous *SMN1* deletion together with three or four *SMN2* copies, but are clinically asymptomatic[20-23]. In seven of these families, we previously identified the Ca^{2+}-dependent protein Plastin 3 (PLS3) as a protective modifier[24; 25]. PLS3 overexpression (OE) rescues SMA across species and is specifically upregulated in MNs of asymptomatic individuals produced from induced pluripotent stem cells[24; 26-29]. Moreover, PLS3 together with the second modifier found in this study, pointed us towards endocytosis as the key disturbed cellular mechanism in SMA[29].

Here, we report the identification of *Neurocalcin delta* (*NCALD*) [MIM: 606722], which encodes a neuronal Ca^{2+} sensor protein, as an SMA protective modifier in humans. We show that NCALD acts as a negative regulator of endocytosis, which is in contrast to PLS3 acting as its positive regulator. We show Ca^{2+}-dependent interaction of NCALD with clathrin, a protein essential in endocytic vesicles coating. We demonstrate that low SMN levels reduce voltage-dependent Ca^{2+} influx and that NCALD binds clathrin at low Ca^{2+} levels, thereby acting as a Ca^{2+}-sensitive inhibitor of endocytosis. Our results, obtained from multiple *in vitro* and *in vivo* systems, show that NCALD suppression reestablishes synaptic function, most likely by restoring endocytosis. Most importantly, we prove that NCALD knockdown (KD) in various SMA animal models ameliorates major functional SMA disturbances, such as motor axon development in zebrafish or MN circuitry and presynaptic function of neuromuscular junction (NMJ) in mice. Moreover, we introduce a mild SMA mouse model generated by combined low-dose SMN-ASO treatment and heterozygous *N*cald knockout, and show restored motoric function. Our data support the notion that genetic modifiers reveal additional valuable treatment options, beyond existing therapies.

MATERIAL AND METHODS

Individuals' DNA, Fibroblast Cell Lines and Lymphoblastoid Cell Lines. Informed written consent was obtained from each subject or their legal guardians for all biological samples according to the Declaration of Helsinki. The study has been approved by the Ethical Committee of University of Cologne (04-138). Human fibroblast and EBV-transformed lymphoblastoid cell lines (LBs) from SMA individuals, carriers and asymptomatic *SMN1*-deleted individuals used in this work are listed in **Table S1.** DNA was extracted from EDTA blood samples, primary fibroblast cell lines and LBs using standard protocols. *SMN1* and *SMN2* copy number were determined by qRT-PCR or MLPA lysis (MRC Holland) as described[30]. For haplotype analysis, polymorphic markers Ag1-CA (D5S1556), C212 (D5F149S1/S2), VS19A (D5S435) and MIT-I105 (D5S351) were analyzed as described[31]. *SMN2* coding region was sequenced in qRT-PCR products obtained from LBs-isolated RNA as described[32]. *PLS3* expression was analyzed as described[24]. All cell lines used were tested for mycoplasma contamination.

Genome-wide Linkage Analysis. Genome-wide scan was performed in 14 individuals of the Utah family using Affymetrix GeneChip Human Mapping 10K Array 2.0, which comprises total 10,024 SNPs with a mean intermarker distance of 258kb, equivalent to 0.36cM (Affymetrix). Parametric linkage analysis was performed by ALLEGRO program[33] assuming autosomal dominant inheritance with full penetrance and 0.0001 disease allele frequency. Haplotypes were reconstructed with ALLEGRO and presented graphically with HaploPainter[34]. All data handling was performed using the graphical user interface ALOHOMORA[35].

Transcriptome Analysis. For expression profiling, 400ng total RNA were amplified and biotinylated using Illumina TotalPrepTMRNA Amplification Kits (Ambion) according to manufacturer's protocol. Human HT-12v3 bead arrays (Illumina) were hybridized with 750ng cRNA for 18h at 58°C according to Illumina Whole-Genome Gene Expression with IntelliHyb

SealSystem Manual. Arrays were washed with E1BC buffer, High-Temp Wash Buffer and 100% ethanol, stained with streptavidine-Cy3, and washed with E1BC buffer. Fluorescence intensities were recorded on BeadArray Reader GX (Illumina). Average signal intensities without background correction[36] were performed with BeadStudio3.1 (Illumina). All data analysis steps were performed in the statistical environment R (version 2.10-0) with several bioconductor packages (version 2.6.1). Signal intensities were normalized with VSN (variance stabilizing and normalization quantification method[37]) and non-informative probes were removed based on p-values. Signals were averaged for individual subgroups and a linear model was designed capturing the influence of the asymptomatic group on gene expression levels[38]. Differences between subgroups were extracted as contrasts and analyzed with the moderated F-test (empirical Bayes method) including a correction step for multiple testing with 5%-FDR-based method[39]. To attribute significant regulations to individual contrasts, a decision matrix was generated based on the function "*decide tests"* within the "*limma*" package, where significant up- or downregulations are represented by values of 1 or -1, respectively.

Targeted Resequencing. To identify a potential variant regulating differential *NCALD* expression, complete *NCALD* locus ±1Mb (chr8:101,505,353-104,404,346) was deep-sequenced from gDNA of family members II-1, III-1, III-4, III-8, and IV-3 at Radboud University Medical Center Nijmegen using a 5500xl sequencing instrument (Life Technologies). ~3Mb genomic DNA from chromosome 8 were captured using a 385K NimbleGen SequenceCapture Array (Roche).

On average, we obtained 2.7Gb of mappable sequence data/individual. Reads were mapped to the hg19 reference genome with LifeTechnologies BioScope software 1.3. On average, 94% of bases originated from the target region (mean 544-fold coverage). 99.8% of the targeted region was covered ≥20 times. Single-nucleotide variants were subsequently high-stringency called by the DiBayes algorithm. Small insertions and deletions were detected using the Small IndelTool. Variants were annotated using an in-house analysis pipeline.

Animal Models

Zebrafish Experiments. All experiments were performed with the transgenic line *tg(mnx1-GFP)*$^{ml2TG\ 40}$ and approved by the local animal protection committee (LANUV NRW; reference number 84-02.04.2012.A251).

Zebrafish Injection and Analysis. Morpholinos (MO) were designed against the translational start codons of respective genes (Gene Tools, LLC). *smn*-MO: 5'-CGACATCTTCTGCACCATTGGC-3'; *ncaldb*-MO: 5'-GGAGCTTGCTGTTTTGTTTTCCCAT-3'; control-MO: 5'-CCTCTTACCTCAGTTACAATTTATA-3'. For *NCALD* mRNA injections, human *NCALD* cDNA was cloned into pCS2+ mRNA expression vector and transcribed *in vitro* using mMESSAGE mMACHINE SP6 Transcription Kit (Ambion) according to manufacturer's protocol. Embryos from TL/EK wildtype and TL/EK-*hb9-GFP*[40] crossings were used to visualize the MN phenotype. Embryos were injected with the respective dose of MOs or mRNA in aqueous solution containing 0.05% PhenolRed and 0.05% Rhodamine-Dextran (Sigma). Six hours after injection embryos were sorted according to homogeneity of the rhodamine fluorescence signal.

Immunohistochemistry for Motor Axon Quantification. 34hpf zebrafish were manually dechorionated, fixed in 4% PFA-PBS and permeabilized by collagenase digest of the whole animal. To visualize the primary motor axons, zebrafish were incubated at 4°C overnight in PBS-T/1%DMSO/10%FCS containing znp-1 antibody (AB2315626, Hybridoma Bank) and stained in PBS-T/1%DMSO/10%FCS containing donkey anti-mouse secondary antibody labelled with AlexaFluor488 (Invitrogen) after all-day washing in PBS-T/1%FCS/1%BSA (changing solution hourly) and stored in 80% glycerol/20% PBS in the dark at 4°C or embedded in low-melting agarose microslides for microscopy analysis. The structure of first ten motor axons posterior to the yolk was analyzed, rated as: 1) normal, 2) truncated (truncation ventral from midline), 3) severely truncated (shorter than midline), 4) branched I (branching ventral

from midline), 5) branched II (branching at midline), or 6) branched III (branching dorsal from midline).

Western Blot Analysis of Zebrafish. 48hpf dechorionated embryos were gently spinned down, sacrificed by incubation on ice and lysed in RIPA buffer (Sigma) containing protease inhibitors (Complete Mini, Roche). The following primary antibodies were used for overnight incubation: anti-beta-actin (zebrafish) (553399, Anaspec), anti-SMN (MANSMA7, Hybridoma Bank; 610646, BD Biosciences) and anti-NCALD (12925-1-AP, Proteintech). Signal detection was performed as described above.

Transmission Electron Microscopy of Zebrafish. 48hpf zebrafish were fixed in 4%PFA for 30min and postfixed in 0.6% glutaraldehyde for another day. Samples were prepared and embedded in resin as previously described[27]. The thickness of semi-thin and ultra-thin sections was 0.5 and 0.1mm, respectively. For immunogold stainings, pre-stained sections were blocked, incubated with primary antibodies (anti-clathrin, (ab273, Abcam), anti-NCALD), washed in PBS and stained with gold-labelled secondary antibodies (donkey-anti-mouse 6nm gold, ab39616, goat-anti-rabbit 20nm gold, ab27237; Abcam). Image acquisition was performed with TEM CM10 (Philips) microscope, Orius SC200W 1 Gatan camera and the Digital Micrograph software.

Motor Behaviour Analysis of Zebrafish. 30 zebrafish treated with respective MOs were placed in 10cm petri dish containing embryo medium. To trigger a swimming response, zebrafish were stimulated with an electrical impulse (60V; delay: 60ms, duration: 4ms, frequency: 6pps (SD9 Stimulator)). Swimming behaviour was recorded with 120 frames/second using a high-speed camera (FC-100, Casio). Swimming velocity and distance were analyzed using LoliTrack software (Loligo Systems).

Endocytosis Inhibitor Treatment. Dynasore (dynamin inhibitor) and Pitstop2 (clathrin inhibitor) (Abcam) were dissolved as stock solutions (50mM) in DMSO. Zebrafish were dechorionated and incubated with the respective inhibitors in the medium starting at 16hpf at 28°C on a rocking platform (20rpm) until fixed in 4%PBS-PFA at 34hpf. Subsequent zebrafish immunohistochemistry was performed as described above.

Electrophysiology. 72hpf zebrafish (control, *smn*-, *ncald*-, and *smn*+*ncald*-morphants) were anesthetized with 0.02% tricaine (in saline; Sigma) for 1-2min and rinsed with saline containing (in mM): 134 NaCl, 2.9 KCl, 2.1 $CaCl_2$, 1.2 $MgCl_2$, 10 HEPES, 10 glucose adjusted to pH7.8. Zebrafish were decapitated and pinned under saline in a Sylgard-coated (Dow Corning) recording chamber (~3ml volume). Skin was removed using a tungsten pin and forceps; preparation was incubated in 3M formamide (in saline; Carl Roth) for 2min to prevent muscle contractions. After rinsing the preparation, the superficial layer of ventral slow muscle cells was removed by scratching with a tungsten pin to expose deeper fast skeletal muscle cells and remaining superficial slow muscles were removed with a low resistance pipette (~2 MΩ). The preparation was continuously superfused with saline at a flow rate of ~2ml/min^{-1}. Experiments were carried out at ~24°C. Muscle cells were visualized with a fixed-stage upright microscope (Zeiss Axio Examiner, Zeiss), using a 40x water immersion objective (Zeiss) with infrared-differential interference contrast and fluorescence optics. Fast muscle cells were identified by their orientation to the spinal cord and ability to generate action potentials.

***Caenorhabditis elegans* Experiments.** *Caenorhabditis elegans strains.* LM99 *smn-1(ok355)I/hT2(I;III)*[41], HA1981 *+/hT2(I;III),* HA2530 *+/hT2(I;III);ncs-1(qa401)X,* HA2531 *smn-1(ok355)I/hT2(I;III);ncs-1(qa401)X*, HA2599 *+/hT2(I;III);uIs72,* HA2623 *smn-1(ok355)I/hT2(I;III);uIs72,* were maintained at 20°C under standard conditions. *+/hT2* strains used as control for genetic background; RNAi studies were undertaken in a sensitized background (transgene *uIs72*) expressing the SID-1 dsRNA channel in neurons[42].

***C. elegans* Pharyngeal Pumping.** Pharyngeal grinder movement in any axis was scored as a pumping event. Average pumping rates (±SEM) were combined from at least three independent trials (n ≥ 25 animals in total). For RNAi knockdown, animals were reared for two generations (F2) on either control vector L4440 or C44C1.3/*ncs-1(RNAi)* in HT115. *ncs-1* RNAi clone contains genomic DNA amplified by primers 5'-AAATCGTCTAGCTGTAGTGTCGC-3' and 5'-TTGTGCTCCCTACACTTTGTTTT-3' inserted into L4440. Clone was verified by sequencing.

Mouse Experiments. All mouse experiments were approved by LANUV NRW (reference number 9.93.2.10.31.07.186 and 84-02.04.2014.A 126). The Taiwanese SMA mice (FVB.Cg-Tg(SMN2)2Hung Smn1tm1Hung/J, Stock Number:005058) and heterozygous *Ncald*$^{ko/wt}$ (Bl6N(Cg)-*Ncald*$^{tm1.1(KOMP)Vlcg}$/J, Stock Number:018575) were purchased from Jackson Laboratory. The severe SMA [*Smn*$^{ko/ko}$*; SMN2*$^{tg/0}$] mice and the corresponding heterozygous *Smn* (HET; [*Smn*$^{kowt-}$*; SMN2*$^{tg/0}$]) mice were produced as previously described[9; 43]. The breeding scheme and genotypes for SMA-*Ncald*$^{ko/wt}$ and HET-*Ncald*$^{ko/wt}$ are similar to SMA+ASO-treated mice (**Figure 5A**), except that all animals were on congenic C57Bl/6N and untreated.

Primers used for mouse genotyping: mmu *Smn*KOfw: ATAACACCACCACTCTTACTC; mmu *Smn*KOrev1: 5`-AGCCTGAAGAACGAGATCAGC-3`; mmu *Smn*KOrev2: 5`-TAGCCGTGATGCCATTGTCA-3`; hsa *SMN2*fw: 5`-CGAATCACTTGAGGGCAGGAGTTTG-3`; hsa *SMN2*rev 5`-AACTGGTGGACATGGCTGTTCATTG-3`; mmu *Ncald*KOfw: 5`-CGGTCGCTACCATTAC-3`; mmu *Ncald*KOrev: 5`-GCATGTGTGACAACAG-3`.

A mild SMA mouse model was produced by suboptimal subcutaneous injection of severe SMA mice (50% FVB/N: 50% C57BL6/N) on P1 with 30µg of SMN-ASO (IONIS Phamaceuticals) using a MICROLITER syringe (Hamilton). The SMN-ASO was diluted as previously described[19]. SMA-*Ncald*$^{ko/wt}$+ASO and HET-*Ncald*$^{ko/wt}$+ASO were produced using the breeding scheme in **Figure 5A**. Unless stated otherwise, all mouse experiments were performed blinded for genotype and treatment.

Mouse Motoric Tests. Righting reflex test was performed as previously described[44]. Righting time scores were evaluated as followed: 0-2s=1; 3-4s=2; 5-6s=3; 7-8s=4; 9-10s=5; ≥11s=6. Muscle strength was assessed in P73 SMN-ASO injected $mixed_{50}$ background mice by the animal's grasp of a horizontal metal bar mounted to a high-precision force sensor (Grip strength meter, TSE Systems). Muscle force was recorded in pounds and converted to Newton [N].

Quantification of Proprioceptive Inputs. Analysis of proprioceptive input on MN soma was performed as described[29]. The spinal cord was dissected from euthanized mice and fixed in 4% PFA overnight. The lumbar L4-L5 region was rinsed in PBS, embedded in tissue freezing medium (Jung) after cryoprotection (first day: 20% sucrose, second day: 30% sucrose) and sliced into 100µm sections (cryostat, Leica). Samples were permeabilized, blocked in PBS/4% BSA/1% Triton/PBS for 1h and incubated with anti-CHAT (Choline acetyltransferase , a MN-specific marker) (AB144P, Millipore) and anti-VGLUT1 (Vesicular glutamate transporter 1 or SLC17A, an excitatory neurotransmitter used for proprioceptive inputs) (135303, Synaptic Systems) antibodies overnight. Samples were washed and incubated with secondary antibodies (donkey anti-rabbit AlexaFluor488, donkey anti-goat AlexaFluor568) and mounted in Mowiol. Images were taken in Z-stacks of 30-60 slices of 0.3µm interval. Proprioceptive input numbers on MN and MN soma size were quantified using the ImageJ software.

Quantification of NMJ Size and Maturity. The *Transversus abdominis* (TVA) muscle was prepared at the indicated time points, fixed in 4%PFA for 20min and stained with anti-NF-M (Neurofilament M, NEFM), used as neuronal axon and dendritic marker, (Hybridoma-Bank)), secondary goat-anti mouse AlexaFluor488 and Bungarotoxin (Invitrogen, labeled with AlexaFluor555). Surface area of Bungarotoxin-positive post-synapse was measured by ImageJ with threshold set to the method established by Li. NMJ immaturity index was analyzed as described previously[45]: NMJs exhibiting ≥ 3 perforations were evaluated as mature, NMJs with < 3 perforations as immature.

FM1-43 Endocytic Uptake at NMJ under Electrical Stimulation. FM1-43 endocytic uptake at NMJ under electrical stimulation was undertaken as recently described[29]. Three animals per genotype and stimulation set were used. Imaging was performed as described above. All imaging processes and analyses were performed double-blinded. Images were analyzed with ImageJ using a macro setting and Li threshold method applied to the postsynaptic terminals to delineate the area of interest in the presynaptic site.

Microscopy. Unless indicated otherwise, all microscopic experiments were performed with a fully motorized fluorescence microscope AxioImager M2 (Zeiss) equipped with an ApoTome. All quantitative measurements were performed using Zen software (Zeiss) and ImageJ and evaluated with indicated statistical packages.

Primary Motor Neuron Culture. Spinal cords were dissected from E13.5 mouse embryos[9]. Neurons were singularized with trypsin (Worthington) and DNAse (Sigma), sieved, plated on poly-D-lysine/laminin (Sigma) coated coverslips and cultured in neurobasal medium with B27 supplement, 2mM L-glutamine, 1x pen-strep (Invitrogen) containing 50ng/µl BDNF, 50ng/µl GCNF and 50ng/µl CNTF (Peprotech) at 37°C in a humidified incubator with 5%CO_2.

Quantitative RT-PCR. RNA was extracted from cell lines using RNeasy kit (Qiagen). 150ng RNA was reversely transcribed to cDNA (Quantitect Reverse Transcription Kit, Qiagen). For *NCALD* cDNA measurements, 9ng cDNA was used for RT-PCR (LightCycler, Roche). RT-PCR was performed in triplicates according to manufacturer's protocol (annealing temperature 68°C, *NCALD* cDNA primers: 5'-GGAATGCCCAGAGCCCCAGTGT-3'; 5'-GCCCCAACCCCCGAGTCTTACG-3'). Standard curve-based absolute transcript quantification was performed using Excel (Microsoft). For statistical evaluation, the Student´s t-test was applied. For quantitative measurements of *SMN* and *PLS3*, previously described protocols were used[24].

siRNA-mediated RNA Knockdown. For all siRNA experiments NSC34 (CLU140)[32] and PC12[46] cells were transfected with Dharmafect1 (Thermo Scientific) according to manufacturer´s protocol. siTOX (Dharmacon) and AllStars Negative Control (Qiagen) siRNA were used as controls. siRNAs sequences: mmu-*Smn: 5'*-AAGAAGGAAAGTGCTCACATA-3'; mmu-*Ncald* 5'-CAGGTGATTCACCCATTATAA-3'; rn-*Smn* 5'-CCCGACCTGTGAAGTAGCTAA-3'; rn-*Ncald* 5'- AGAGACTTCCTAGCAATTTAA-3. After incubation, cells were harvested for protein isolation or imaging. Every experiment was performed at least in triplicates.

Transient Overexpression. Human *NCALD* cDNA was cloned into pcDNA™3.1/CT-GFP TOPO using primers NCALD-FWD 5'-ATGGGGAAACAGAACAGCAAG-3' and NCALD-REV 5'-GAACTGGCCGGCACTGCTC-3' (IDT) and manufacturer's protocol (Invitrogen). To overexpress human NCALD-GFP, NSC34 cells were transfected with Dharmafect1 according to manufacturer´s protocol.

Western Blot Analysis. Cells were lysed on ice in RIPA buffer (Sigma) containing protease inhibitors (Complete Mini, Roche). The following primary antibodies were used: anti-ACTB (actin, beta), used as control for equal loading (A5316, Sigma), anti-SMN (MANSMA7, Hybridoma Bank; 610646, BD Biosciences), anti-NCALD (12925-1-AP, Proteintech) and anti-CLTC (clathrin heavy chain) (C1860, Sigma). Signal was detected with HRP conjugated-secondary antibodies and Chemiluminescence reagent (Thermo Scientific) according to manufacturer´s protocol.

NCALD Co-immunoprecipitation. NSC34 cells transiently transfected with pcDNA/FLAG-His-NCALD or control vector were lysed in the following buffer: 50mM Tris/HCl, 5% (w/v) glycerol, 270mM sucrose, 0.5%(v/v) Tween 20, 0.1%(v/v) β-mercaptoethanol, pH7.5, with protease inhibitor cocktail (Complete Mini, EDTA-free, Roche). Immunoprecipitations were

performed in 1mM EGTA/1mM EDTA or in the presence of 100µM free Ca^{2+}. Cell lysates were immunoprecipitated with FLAG-M2 affinity beads (Sigma) under gentle agitation overnight at 4°C. Bound proteins were eluted in laemmli buffer (240mM Tris-HCl, pH6.8, 6% SDS, 30% (v/v) glycerol, 0.06% bromophenol blue (w/v), 16%(v/v) β-mercaptoethanol) and analyzed by Western blots as described above.

Immunocytochemistry. Cells were cultured on laminin-coated coverslips, washed with PBS, fixed in 4%PFA/4%sucrose (AppliChem), permeabilized in PBS-T (PBS/0.2%Tween20 (AppliChem)) and blocked in blocking solution (PBS-T/5%BSA (Sigma)/5%FCS (Biochrom)). Cells were incubated with blocking solution containing primary antibodies (α-HB9, homeobox 9; used as MN-specific marker, (1:100), AB2145209, Hybridoma Bank; α-SV2 (Synaptic vesicle glycoprotein 2, used as synaptic vesicle marker AB2315387, (SV2-c), Hybridoma Bank; α-NF- M, AB2314897, (2H3-c), Hybridoma Bank; α- CHAT, AB144P, Millipore; α-Tau (axon-specific marker), sc-390476, Santa Cruz; α-NCALD) overnight at 4°C. After washing in PBS, cells were incubated with secondary antibodies labelled with AlexaFluor488, AlexaFluor647 or AlexaFluor568 (Invitrogen) in PBS, optionally with phalloidin-AlexaFluor568 (Invitrogen). Cells were washed and mounted on objects slides with Mowiol (Sigma) for imaging.

Endocytosis Assay. Fibroblasts were plated in DMEM (Invitrogen) and starved for 10min in starvation media (DMEM transparent (HEPES), 2%FKS) prior to fluorescein isothiocyanate (FITC)-Dextran treatment (5mg/ml, Sigma) for respective time periods at 37°C. Subsequently, cells were washed with ice-cold PBS and fixed in 4%PFA for 10min. After washing, cells were stained with phalloidin-AlexaFluor568 and DAPI (Invitrogen) and mounted with Mowiol for imaging.

Flow Cytometry Analysis. NSC34 cells were transfected with indicated siRNAs for 48h prior to 6h starvation and incubation with 5mg/ml FITC-Dextran (Sigma) for 20min at 37°C. Cells were trypsinized (Trypsin, Sigma) on ice and washed with PBS. Uptake of FITC-Dextran was

measured with FACS Calibur (BD Biosciences) and analyzed with Cyflogic software (CyFlo Ltd.). Dead cells were excluded by propidium iodide staining (10µg/ml, Sigma).

Ca^{2+} Current Recordings in NSC34 and PC12. Whole-cell recordings were performed at 24°C. Electrodes (tip resistance 2.5-3 MΩ) were made of borosilicate glass (0.86mm OD, 1.5mm ID, Science Products) with a temperature-controlled pipette puller (PIP5, HEKA Elektronik) and filled with solution containing (in mM) 133 CsCl, 1 $CaCl_2$, 2 $MgCl_2$, 10 HEPES and 10 EGTA, adjusted to pH7.2 and osmolarity of 415mOsm. During experiments, cells were constantly superfused with saline solution containing (in mM) 84 NaCl, 20 CsCl, 2.5 KCl, 10 $CaCl_2$, 2 $MgCl_2$, 10 HEPES and 30 glucose, adjusted to pH7.3 and osmolarity of 310mOsm. To isolate Ca^{2+} currents, a combination of pharmacological blockers and ion substitution were used. Transient voltage-gated Na^+ currents were blocked by tetrodotoxin (10^{-6}M TTX, T-550, Alomone). 4-Aminopyridine (4AP, 4×10^{-3}M, A78403, Sigma) blocked transient K^+ currents (I_A) and tetraethylammonium (TEA, 2×10-3, Sigma) blocked sustained K^+ currents ($I_{K(V)}$) and Ca^{2+}-activated K^+ currents ($I_{K(Ca)}$). The pipette solution did not contain potassium. Whole-cell voltage-clamp recordings were made with EPC10 patch-clamp amplifier (HEKA Elektronik) controlled by Patchmaster program (V2x53, HEKA-Elektronik). Electrophysiological signals were low-pass filtered at 2.9kHz (3pole Bessel filter). Data were sampled at 50µs intervals (20kHz). The offset-potential and capacitance were compensated using 'automatic mode' of EPC10 and liquid-junction potential between intracellular and extracellular solution of 2.5mV (calculated with Patcher's PowerTools plug-in) was compensated. Whole-cell capacitance was determined using EPC10 capacitance compensation (C-slow). To remove uncompensated leakage and capacitive currents, p/6 protocol was used[47]. Voltage errors due to series resistance (RS) were minimized using RS compensation of EPC10 to 70-80% with 100µs time constant (τ).

Statistical Analysis. If not mentioned otherwise, all statistical analyses were performed using software programs Excel 2013 (Microsoft), GraphPad Prism 6 (GraphPad Software) and

Sigma Plot 11 (Systat Software); ANOVA, Mann-Whitney U-test, Fisher´s exact test or unpaired two-tailed Student's t-tests were applied. All data are represented as mean±SEM/SD. Significance of RNA expression and protein levels was tested using a directional student's t-test for uncorrelated samples. For experiments performed in *C. elegans*, Mann-Whitney-U test was performed. Significance in the differences of mouse behavioral analyses, NMJ and muscle fiber surface area size, motor axon length, proprioceptive inputs on MNs, NSC34 neurite length and width of the synaptic cleft was determined by the use of 1-way ANOVA or directional student's t-test for uncorrelated samples. Survival was analyzed using Kaplan-Meier method by log rank test.

For all studies using mice, animals numbers were calculated prior to experiments by power calculation using the G*Power 3.1.7 software (Power=0.8 and alpha-error=0.05). Endpoint criteria for mouse experiments were defined in animal application prior to experiments. Animal samples were processed equally and allocated to experimental groups post-analysis. For all other experiments, sample size was estimated based on the known variability of the assay.

Values of $P<0.05$ were considered significant. In all cases, three levels of statistical significance were distinguished: *$P<0.05$, **$P<0.01$ and ***$P<0.001$.

Specific statistical tests, sample size and P-values are indicated in the figure legends.

Statistical Analysis of Electrophysiology. Data were analyzed using Spike2 and statistical analysis was performed in GraphPad Prism 5.05 (GraphPad Software). All calculated values are shown as mean±SEM. The EEP frequencies for each cell were measured as mean frequencies over 30s intervals. Frequencies before and during NMDA application were compared by a paired t-test for each group. Kruskal-Wallis test followed by Dunns multiple comparisons was used to compare EPP frequencies in different groups. A significance level of $P<0.05$ was accepted for all tests.

RESULTS

Identification of NCALD as a Potential SMA Modifier by Genome-Wide Linkage and Transcriptome-Wide Differential Expression Analysis

In a four-generation Mormon family from Utah, we identified seven individuals carrying homozygous *SMN1* deletions, two affected by type 1 SMA and five fully asymptomatic, except for increased photosensitivity (**Figure 1A**) (See Supplemental Information for full clinical investigation description of Utah family members).

Haplotype analysis of SMA regions showed a co-segregation of three different SMA alleles (**Figure 1A**). The two type 1 SMA individuals carried no *SMN1* and two *SMN2* copies. By contrast, all five asymptomatic individuals showed homozygous absence of *SMN1* and presence of four *SMN2* copies, resembling a genotype associated with type 3 SMA[13] (**Figure 1A**). *SMN2* sequencing excluded any further variants affecting expression. In lymphoblastoid cells (LBs), SMN RNA and protein levels were similar to those in typical type 3 SMA individuals, thus excluding *cis* and *trans*-acting factors regulating *SMN2*. Increased *PLS3* expression was not found (**Figure 1A**, GEO: GSE58316). Thus, we concluded that a previously unknown SMA modifier potentially protects these individuals.

To identify the SMA modifier, we combined linkage with transcriptome-wide differential expression analysis. Assuming a dominant mode of inheritance, a parametric linkage analysis with 14 family members revealed eight positive peaks with a maximum LOD score of 1.5 (**Figure 1B**). In parallel, a transcriptome-wide differential expression analysis with 12 total RNA samples was performed (GEO: GSE58316) and revealed 17 transcripts significantly differentially regulated in asymptomatic individuals (**Table S2**). *NCALD* was represented by two independent hybridization probes on the array, both showing a 4-to-5 fold downregulation in the asymptomatic group *versus* familial type 1 SMA or an independent type 3 SMA group. Most importantly, *NCALD* was the only transcript localized in one of the eight linked regions

on chromosome 8q22.3 (between rs28144 and rs958381), making it a highly likely candidate. Microarray data were confirmed by RT-qPCR and Western blot (**Figure 1C and 1D**).

To search for the potential genetic mechanisms involved in reduced *NCALD* expression, targeted resequencing of ~3 Mb genomic DNA encompassing *NCALD* in five family members was carried out. On average 2,723 variants were called per sample. Based on previous haplotype data, we filtered for heterozygous variants shared between individuals II-1, III-1, III-4, IV-3, but absent in III-8. This yielded 43 variants (21 previously annotated SNPs), none of which were in the *NCALD* coding region. Only the SNP rs147264092 in intron1 with a minor allele frequency=0.1079 (1000Genome database) was located in *NCALD* UTR (**Table S3**). ~600kb upstream of *NCALD* we identified a 17bp deletion (nt103783522-38, rs150254064; MAF=0.056 in 1000Genome database) perfectly segregating with the modifier haplotype (**Figure S1**) that seemed interesting. The 17 bp deletion is localized adjacent to an H3K27AC block and a super enhancer (ENCODE), which may influence *NCALD* expression. We hypothesize that the combination of both variants acts on *NCALD* expression (Wirth, unpublished data). Both variants were further analyzed in 50 *SMN1*-deleted individuals, who were chosen because of a discrepant SMA severity according to their *SMN2* copy number and 65 controls. The combination of both variants was found in one individual, who unexpectedly carried only one *SMN2* copy. This genotype is regarded as a type 0 SMA with death in utero or immediately after birth[48]. In contrast, this individual survived 9 months, suggesting a potential protection by a genetic modifier, which could be *NCALD*. No LBs were available to test expression. The combination of both variants on a haplotype is a very rare event 0.003 (13/5008 haplotypes included in the Phase 3 1000Genome project, see LDlink). Since homozygous deletions of *SMN1* occur with a frequency of 1:6,000 to 1:20,000 depending on ethnicity[49], the combination of homozygous *SMN1* deletion and the chromosome 8 modifier haplotype would statistically occur in less than 1:8,000,000 people. Further work is in progress, to fully understand the impact of these variants on chromatin structure and *NCALD* expression. However, since understanding gene regulation and the interplay between cis and trans-regulatory elements is extremely challenging and may not yield solid results, we decided to

take the direct approach and analyzed the impact of NCALD reduction in four different SMA animal models: *C. elegans*, zebrafish, a severe and a mild SMA mouse model.

NCALD is one of 14 neuronal calcium sensor (NCS) proteins in mammals. These proteins are highly conserved across species and primarily involved in neuronal Ca^{2+} signaling[50; 51]. *NCALD* encodes a ~22 kDa protein that contains two pairs of EF-hand domains and an N-terminal myristoyl anchor, which enables switching from cytosolic to membrane-bound forms in a Ca^{2+}-dependent manner[52; 53]. A Ca^{2+}-dependent mobility shift of both myristoylated and non-myristoylated forms was reported[54]. NCALD is highly abundant in cerebral neurons, spinal MNs, and in axonal growth cones[55]. NCALD overexpression inhibits neurite outgrowth[56]. NCALD is important in phototransduction[57], which may explain photosensitivity in asymptomatic individuals. Importantly, NCALD interacts with clathrin and actin, both of which are involved in endocytosis and synaptic vesicle recycling[58; 59].

NCALD Knockdown Triggers MN Differentiation and Restores Neurite and Axonal Growth in SMA

First, we analyzed NCALD expression levels during MN differentiation and maturation in NSC34 cells treated with retinoic acid (RA)[60] to induce differentiation and observed a steady increase in NCALD amount over time under RA treatment (**Figure 2A**). siRNA-mediated *Ncald* reduction (**Figure S2A)** induced MN differentiation (indicated by HB9-positive staining) and triggered neurite outgrowth even without RA treatment (**Figure 2B**). In contrast, NCALD overexpression in RA-treated NSC34 cells impaired neurite outgrowth (**Figure S2B and S2C**). NCALD is highly abundant in axonal growth cones of spinal MNs[55]. In addition, we show that it localizes at the presynaptic terminals of NMJs, suggesting a potential role at the NMJ (**Figure S2D and S2E**).

We found that *Ncald* knockdown in *Smn* deficient NSC34 cells restored impaired neurite outgrowth to controls levels (**Figure S2E**). Similar results were obtained in cultured primary MNs from SMA ($Smn^{ko/ko}$;$SMN2^{tg/0}$) versus HET ($Smn^{ko/wt}$;$SMN2^{tg/0}$) embryos, where reduced

axon length of SMA MNs[61] was restored by siRNA-mediated *Ncald* knockdown (**Figure 2C**). These findings indicate that reduced NCALD levels counteract the impaired axonal development of SMN-deficient MNs.

ncald Knockdown Restores Axonal Growth and NMJ Functionality in Zebrafish *smn* Morphants

Human NCALD and its ortholog in zebrafish are 98% identical, suggesting important conserved functions across species. We next investigated the modifying effect of *ncald in vivo* in a *mnx1:eGFP*-expressing zebrafish line[40] by MO-mediated knockdown of either *smn, ncald* or both together. Consistent with previous results, *smn* depletion resulted in motor axon-specific outgrowth defects, such as truncations and ectopic branches[24; 62] (**Figure 3A**). Knockdown of *ncald* led to enhanced motor axons branching, whereas double *smn+ncald* knockdown fully rescued the truncated motor axon defect associated with Smn deficiency (**Figure 3A, 3C and S3A**). Knockdown efficiency was confirmed by Western blot (**Figure 3B**). We also found that overexpression of human *NCALD* mRNA in wildtype zebrafish caused truncation and branching of motor axons (**Figure S3B**), resembling the phenotype of *smn* morphant zebrafish (**Figure 3A**) similar to NSC34 cells (**Figure S2C**).

During NMJ maturation the width of the synaptic cleft is increasing, which is essential in neurotransmission[63]. Ultrastructural analysis of the synaptic cleft revealed an impaired NMJ maturation in *smn* morphants (**Figure 3D and 3E**). The width of the synaptic cleft in *smn* morphants was significantly smaller than in controls or *ncald* morphants; double *smn+ncald* knockdown significantly restored synaptic maturation, resulting in a cleft width similar to control embryos (**Figure 3D and 3E**).

To test the functionality of neuromuscular synapses between caudal primary MNs and ventral fast muscle cells[64], we performed whole-cell patch clamp recordings from muscle cells during MN stimulation in control (ctrl), *smn*, *ncald,* and *smn+ncald* zebrafish morphants. We recorded spontaneous endplate potentials at rest (without stimulation) and during MN stimulation by

NMDA (N-methyl-D-aspartate, agonist of NMDA receptors) (**Figure S3C**). In controls, we recorded at rest small endplate potentials that were primarily not tetrodotoxin (TTX) sensitive (**Figure S3D and S3E**) and mostly resembled miniature endplate potentials (mEPPs)[65]. During NMDA stimulation, the mEPP frequency did not significantly increase, but large TTX-sensitive endplate potentials and muscle action potentials were induced by MN spike evoked transmission. In *smn* morphants, a significantly lower spontaneous mEPP frequency and only occasional action potentials during NMDA stimulation were observed (**Figure 3F**). In the *smn+ncald* morphants, the spontaneous mEPP frequency was slightly increased and the frequency of large NMDA-induced EPP was restored to control levels (**Figure 3F and 3G**). In line with the electrophysiological data, swimming velocity after electrical stimulation was reduced in *smn* morphants, but rescued in *smn+ncald* morphants (**Figure S3F**). Together, these results show that Ncald knockdown rescues neural circuit function at the NMJs of *smn* morphants.

Loss of NCALD Ortholog Suppresses Defects of *C. elegans* SMA Model

C. elegans lacking the *SMN* ortholog *smn-1*, referred to here as *Cesmn-1,* show neuromuscular defects, including decreased pharyngeal pumping rate (**Figure S4A**)[26; 41]. The *C. elegans* ortholog of *NCALD* is encoded by neuronal calcium sensor-1 (*ncs-1*)[66]. Either *ncs-1* knockdown by RNA interference or introduction of the *ncs-1(qa401)* loss of function allele in *Cesmn-1* animals, significantly ameliorated pumping defects (**Figure S4B and S4C**), confirming that NCALD loss ameliorates the SMN loss-of-function-induced neuromuscular defects across species.

Heterozygous *Ncald* KO Ameliorates Motor Neuron Development in Severe SMA Mice

We took advantage of an *Ncald* knockout mouse (*Ncald*$^{ko/ko}$) recently generated by the Knockout Mouse Phenotyping Program at the Jackson Laboratory. Heterozygous *Ncald*$^{ko/wt}$ mice are asymptomatic and show >50% reduction of NCALD levels in spinal cord and brain

(**Figure 4A**). Homozygous *Ncald*$^{ko/ko}$ mice are viable and fertile; however, preliminary reported data by the International Mouse Phenotype Consortium (IPMC) (online mouse phenotype data base) and our data revealed behavioral abnormalities, vision defects and metabolic impairment. In contrast, heterozygous *Ncald*$^{ko/wt}$ mice showed no gross morphological or behavioral problems even at 18 months of age. Since asymptomatic individuals show reduced, but not full loss of NCALD, we used the heterozygous *Ncald*$^{ko/wt}$ animals for all further experiments herein.

The *Ncald*$^{ko/wt}$ allele was bred into a severe SMA mouse model[9] on pure C57BL/6N background. Both SMA and SMA-*Ncald*$^{ko/wt}$ mice die at a mean age of 13 days and there is no difference in weight progression at this age (**Figure S5A and S5B**). Severe SMA mice show multi-organ failure[27; 43; 67] due to very low SMN levels, which could not be rescued by heterozygous *Ncald* knockout alone. Nonetheless, we found that other hallmarks of SMA were improved upon heterozygous *Ncald* knockout: the size of the NMJs in the *Transversus abdominis* muscle (TVA) was increased and the number of proprioceptive inputs on MN soma was elevated in SMA-*Ncald*$^{ko/wt}$ versus SMA mice (P10) (**Figure 4B and 4C**). Moreover, SMA-*Ncald*$^{ko/wt}$ mice showed more inputs per MN than SMA mice independent of cell size (**Figure S5C**). A comparison of axonal development in cultured primary MNs revealed a large impact of NCALD reduction on axonal growth and arborization (**Figure 4D**), confirming our initial results with siRNA-mediated *Ncald* knockdown (**Figure 2C**). Therefore, NCALD reduction counteracts impaired axonal development and restores NMJ size in SMN-deficient mice, but is not able to improve survival due to severe multiple organ impairment.

Combinatorial Therapy with a Suboptimal Low-dose SMN-ASO and Reduced *Ncald* Expression Ameliorates SMA Pathogenesis in a Severe SMA Mouse Model

In our study, we combined suboptimal low-dose SMN-ASOs with heterozygous *Ncald* knockout mice for four reasons: i) asymptomatic individuals carry four *SMN2* copies similar to typical type 3 SMA individuals, but not two *SMN2* copies as our severe SMA mouse model or most

type 1 SMA individuals; ii) genetic modifiers efficiently protect against SMA only if a sufficient SMN level is present to suppress inner organ dysfunction[29]; iii) NCALD expression is mainly restricted to neuronal tissues, therefore its beneficial effect is directed to MN, but cannot improve other peripheral organs affected in severe type of SMA, and iv) type 1 SMA individuals, currently treated with SMN-ASOs, show only a moderate SMN elevation, and may need additional drugs/molecules supporting MN function. For these reasons, we chose to establish a mild SMA mouse model that shows no impairment in lifespan or peripheral organs, but has a prominent motoneuronal phenotype. Since presymptomatic subcutaneous (s.c.) injection of high dose SMN-ASO in severely-affected SMA mice fully rescues SMA[68], and low dose SMN-ASO in C57BL6/N congenic mice increased survival to only 1 month (intermediate phenotype)[29], we opted for a different strategy to produce a mild SMA phenotype. We crossed C57BL/6N *Ncald*$^{ko/wt}$*;Smn*$^{ko/wt}$ males with FVB/N *Smn*$^{ko/ko}$;*SMN*$^{tg/tg}$ females to produce 50% C57BL/6N:50% FVB/N (mixed$_{50}$) offspring (**Figure 5A**). This breeding strategy was already performed previously and showed increased lifespan and more robustness when compared to pure C57BL6/N or FVB/N mice[27]. However, almost as expected, untreated mixed$_{50}$ SMA and SMA-*Ncald*$^{ko/wt}$ mice live 16.5 and 17.0 days, respectively, showing that the modifier alone is still unable to counteract the massive loss of SMN (**Figure 5B**). Therefore, mixed$_{50}$ offspring were injected s.c. with a single suboptimal dose (30µg) of SMN-ASO on P1. Elevated SMN levels were obtained in liver, but not in spinal cord or brain (**Figure S6A**). Survival of SMA+ASO mice was rescued (**Figure 5B**), but their motoric abilities were visibly impaired as determined by righting reflex and grip strength tests (**Figure 5C and 5D**). This suggests that slightly elevated SMN levels achieved by systemic SMN-ASO treatment rescued non-neuronal multi-organ impairment[29], but not MN function. In contrast, heterozygous *Ncald* knockout, in addition to low dose SMN-ASO treatment, significantly improved motoric abilities (**Figure 5C and 5D**). Analysis of NMJs maturation score on P21[45] showed that both NMJ size and maturation were markedly restored by *Ncald* reduction as compared to SMA+ASO mice (**Figure 5E**). Heterogyous *Ncald* knockout did not rescue tail necrosis and slightly impacted weight progression in male mice (**Figure S6B, S6C and S6D**). Our data provide conclusive evidence

of the beneficial effect of reduced NCALD on the neuromuscular system and motoric function in SMA+ASO mice.

Low SMN Decreases Ca^{2+} Influx in NSC34 and PC12 Cells

Since NCALD is a neuronal Ca^{2+} sensor, and impaired Ca^{2+} homeostasis has been reported in SMA[69], we tested if lowering SMN and NCALD levels could modulate voltage-dependent Ca^{2+} currents (I_{Ca}) in MN-like cells. We performed whole-cell patch-clamp recordings and ratiometric Ca^{2+} imaging with fura-2. We recorded I_{Ca} of RA-differentiated NSC34 cells that were treated with siRNAs specific to *Smn*, *Ncald*, or *Smn*+*Ncald* and analyzed the I_{Ca} tail currents with a series of increasing voltage pulses. In NSC34 cells, *Smn* depletion significantly reduced the voltage-dependent Ca^{2+} influx, which was not restored by additional *Ncald* reduction (**Figure 6A**). Ratiometric Ca^{2+} imaging with fura-2 revealed a reduced voltage-dependent Ca^{2+} influx in SMN-depleted PC12 cells compared to controls (**Figure S7A**). These data show that low SMN levels impair Ca^{2+} influx, which is not restored by NCALD knockdown and that NCALD depletion rescues synaptic transmission through a different mechanism.

Disturbed Endocytosis and Synaptic Vesicle Recycling is Ameliorated by NCALD Depletion

We next sought for a common pathway in which both SMA modifiers, NCALD and PLS3, might operate. Since NCALD binds clathrin directly[58] and PLS3 knockout in yeast impairs endocytosis[58; 70], we hypothesized that low SMN levels may impair endocytosis, which in turn is rescued by reduced NCALD or increased PLS3 levels. Indeed, we recently reported impaired endocytosis as a disturbed cellular mechanism affected in SMA, which is rescued by elevated PLS3 levels[29]. Impaired endocytosis and endocytic trafficking have further been demonstrated in a *C. elegans* SMA model[71].

Co-immunoprecipitation studies in NSC34 revealed NCALD interaction with clathrin only in the absence of Ca^{2+} (**Figure 6B**) or at low Ca^{2+} levels (data not shown). TEM analyses after

immunogold staining of wild type zebrafish sections showed co-localization of Ncald and clathrin in the presynaptic sites of NMJs (**Figure S7B**).

To study the effect of NCALD on endocytosis, we undertook FITC-dextran internalization assays in various cell culture systems. In primary fibroblast cell lines derived from SMA individuals, endocytosis rates were strongly reduced compared to controls, but were restored in fibroblasts of asymptomatic individuals (**Figure 6C and S7C**). Moreover, *Smn* knockdown in NSC34 cells significantly reduced FITC-dextran uptake, which was rescued by concomitant *Ncald* knockdown. *Ncald* knockdown alone increased the rate of endocytosis by 1.3-fold, demonstrating that low NCALD levels already facilitate endocytosis (**Figure S7F**).

Moreover, we analyzed endocytic uptake of FM1-43 in mouse NMJs under stimulation at 5 and 20 Hz as described[29]. FM1-43 uptake was markedly decreased in SMA mice at 5 Hz stimulation (triggering clathrin-dependent endocytosis), but heterozygous *Ncald* knockout fully restored the levels similar to HET mice (**Figure 6D and S7D**). Heterozygous *Ncald* knockout had no impact at 20 Hz stimulation (triggering bulk endocytosis), further strengthening the specific role of NCALD in the clathrin-dependent endocytosis at the NMJ (**Figure S7E**).

Lastly, we investigated *in vivo* the mutual effect of endocytosis and the Smn-Ncald-clathrin network for SMA using pharmacological inhibition of endocytosis in zebrafish. Using sub-phenotypical concentrations of either *smn* MO (2 ng) or a suboptimal dose of Pitstop2 (12.5 µM), an inhibitor of clathrin[72], showed almost no axon truncation and branching phenotype as compared to higher concentrations of *smn* MO (4 ng, **Figure 3A and 3C**) or Pitstop2 (25 µM, **Figure S7G**). Instead, combination of suboptimal *smn* MO (2ng) together with suboptimal Pitstop2 (12.5 µM) resulted in severe motor axons truncation, suggesting a synergistic effect. Notably, this SMA phenotype was strongly ameliorated by additional *Ncald* reduction (**Figure 6E**), (**Figure 3A and 3C**). Moreover, the treatment with Dynasore (25 µM), an inhibitor of the endocytosis-driving GTPase dynamin[73], either alone or in combination with low *smn* MO, resulted in an SMA-like axonal truncation (**Figure 6E**). These defects were ameliorated by additional treatment with *ncald* MO (**Figure 6E and S7G**). Together, these findings suggest

that SMN and clathrin interact genetically to promote endocytosis and MN axonogenesis, whereas NCALD negatively interferes with an SMN-dependent function of clathrin.

DISCUSSION

Here, we describe NCALD as a genetic SMA modifier in humans. In summary, we show that 1) reduced NCALD levels protects individuals from developing SMA, despite lacking *SMN1* and carrying only four *SMN2* copies, usually causing type 3 SMA[13]. Thus, unlike PLS3, which alleviates SMA pathology upon overexpression[24], NCALD reduction acts as a genetic suppressor of SMA; 2) NCALD is localized at SMA relevant sites including MN soma and growth cones as well as the presynaptic site of the NMJ. Furthermore, NCALD knockdown is relevant for MN differentiation and restores neurite and axon outgrowth in MNs or MN-like cells; 3) NCALD has a Ca^{2+}-dependent interaction with clathrin and is thereby able to modulate endocytosis, and likely vesicle recycling at the motor endplate; 4) NCALD knockdown rescues neural circuit function of zebrafish *smn* morphants by restoring axonal outgrowth defects, endplate potentials and swimming velocity; 5) *ncs-1* knockdown in *smn-1* deficient *C. elegans* restores pumping to normal rates; 6) Heterozygous NCALD knockout in severely or intermediately affected SMA mice causes clear improvements on the structural level, such as NMJ size and architecture, MN outgrowth and proprioceptive inputs; 7) Heterozygous NCALD knockout in mild SMA mice with no lifespan impairment has beneficial effects on NMJ size and architecture as well as motoric abilities. Finally, 8) across species, the mechanism by which reduced NCALD level improves SMA pathology is restoration of endocytic function, strengthening the existing models holding endocytosis as a main impaired cellular mechanism in SMA.

NCALD Downregulation as a Potential Therapy in Combinatorial Approach

Clinical trials using ASOs to correct *SMN2* splicing are highly promising and close to FDA-approval[2]. However, for type 1 SMA children with only two *SMN2* copies, these approaches

are likely insufficient to fully suppress SMA symptoms. It is also unclear, to which extent the elevation of SMN after disease onset will be able to protect from SMA and whether combinatorial therapies including SMN-dependent and SMN-independent pathways will be required to achieve full and long-term rescue[74]. There is increasing evidence – at least in mouse models – that systemic SMN elevation is required to fully counteract SMA; systemic injection of SMN-ASOs or AAV9-SMN led to a robust survival increase in various SMA mouse models in comparison to a central nervous system (CNS) restricted application[68; 75]. This is in line with the observation that additional non-neuronal organs and tissues are impaired in severe SMA mouse models and partially in type 1 SMA individuals (reviewed in[18; 76]).

Recently, we have shown that PLS3 overexpression in combination with low SMN elevation using SMN-ASOs[68] increased the survival of severely affected SMA mice from 14 to >250 days[29]. This might resemble a hypothetic situation in which individuals with type 1 SMA are treated with a molecule/drug that increases SMN levels acting on the endogenous *SMN2* copies in combination with an additional molecule/drug acting on the genetic modifier. In contrast to PLS3, the effect of NCALD was less pronounced, which is in line with the observation that asymptomatic individuals protected by reduced NCALD require the presence of four *SMN2* copies, while in case of elevated PLS3 three *SMN2* copies are sufficient[24; 25]. In addition, the limited effect of NCALD might be due to the restricted expression in neuronal tissues as compared to PLS3, which is ubiquitously present. Moreover, the broader impact of PLS3 on F-actin dynamics that influences various cellular processes at NMJ level[27; 29] may further contribute to the more prominent protection.

Nonetheless, a combinatorial therapy that both elevates SMN and decreases NCALD (*e.g.* by ASO treatment) may provide a full protection, resulting in asymptomatic individuals. The advantage of NCALD, in comparison to PLS3, is that suppression of gene function is, in general, easier to achieved than its activation.

NCALD Suppression Restores Endocytosis and Synaptic Vesicle Recycling in SMA

To allow rapid and repeated rounds of neurotransmission at the synaptic endplate, synaptic vesicle recycling is essential[77]. In brief, after Ca^{2+}-dependent exocytosis and release of acetylcholine (ACh) into the synaptic cleft, the synaptic membrane has to be retrieved rapidly *via* endocytosis. Then, retrieved vesicular membranes need to be transformed into synaptic vesicles, which are refilled with ACh. These are eventually transported to the readily releasable pool near active zones[78]. Despite the robust fail-safe factor in the motor neuron endplate potential, disturbances in the presynaptic vesicle cycle can severely impact neurotransmission. In SMA, impaired neurotransmission, disturbed Ca^{2+} homeostasis, decreased synaptic vesicle number, and reduced F-actin caging of reserve pool synaptic vesicles have been reported[16; 69; 79; 80]. For repeated neurotransmitter release, subsequent endocytosis is important[81]; furthermore, endo- and exocytosis are regulated by the Ca^{2+} dynamics within the presynaptic terminals[82].

We found that low SMN levels cause reduction of voltage-activated Ca^{2+} influx, in accordance with recent studies in a zebrafish SMA model and reported mislocalization of calcium channels in SMA[83; 84]. However, unlike SMA pathology, Ca^{2+} influx was not restored by reduced NCALD, suggesting a different counteraction mechanism. Since NCALD interacts with clathrin and actin, two major players in endocytosis[58; 59], we hypothesized that reduced SMN may disturb endocytosis and synaptic vesicle recycling, possibly via decreased Ca^{2+}, whereas NCALD knockdown subsequently compensates for SMN loss. We demonstrate *in vitro* and in *ex vivo* mouse NMJs that NCALD reduction restores impaired clathrin-dependent endocytosis. Furthermore, chemical endocytosis inhibition in zebrafish caused MN axonogenesis defects that were reversed upon Ncald suppression. Importantly, NCALD binds clathrin only at low Ca^{2+} levels (mimicking unstimulated MNs) but not at high Ca^{2+} levels (mimicking action potentials in MNs). For SMA MNs, with low Ca^{2+} levels even during action potential, we predict that NCALD constantly binds clathrin, thereby inhibiting/reducing NCALD function in synaptic vesicle recycling. However, low NCALD levels, as in asymptomatic individuals, may allow free clathrin to act in endocytosis and synaptic vesicle recycling even at reduced Ca^{2+} levels (**Figure 7**).

Implication of NCALD in other Neurodegenerative Disorders

In agreement with this hypothesis, two other proteins connected to endocytosis cause various forms of SMA. Mutations in *UBA1* [MIM: 314370], an E1 Ubiquitin-Activating Enzyme involved in monoubiquitination which serves as a signal for endocytosis and trafficking of cell surface proteins, has been associated to X-linked SMA (SMAX2 [MIM: 301830])[85-87]. *BICD2* [MIM: 609797], which when mutated, causes autosomal-dominant lower-extremity-predominant spinal muscular atrophy-2 (SMALED2 [MIM: 615290]), binds to clathrin heavy chain to promote its transport and augments synaptic vesicle recycling[88-92]. These findings provide additional evidence that disturbances in synaptic vesicle recycling underlie general SMA pathology. Our findings are further strongly supported by data in *C. elegans*, in which disturbed endocytic trafficking at synaptic level has been reported, and it has been suggested that an increased resistance against infection may explain the high SMA carrier frequency in the population[93]. Moreover, reduced NCALD amount might be beneficial for other MN or neurodegenerative disorders with impaired endocytosis and Ca^{2+}-homeostasis, as was shown for Alzheimer´s (AD [MIM: 104300]), where NCALD is highly upregulated[94], or Parkinson´s (PD [MIM: 168600]), hereditary spastic paraplegia [MIM: PS303350] and ALS [MIM: PS105400], where impaired endocytic trafficking was found[95]. Therefore, it is tempting to speculate that NCALD downregulation might become an efficient strategy against SMA and other neurodegenerative diseases.

SUPPLEMENTAL DATA DESCRIPTION

Supplemental Data includes seven figures, three tables and clinical description of Utah family members.

Accession codes.

Gene Expression Omnibus: all microarray data are available in GSE58316.

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Web Resources

Statistical environment R, http://www.r-project.org

Bioconductor packages, https://www.bioconductor.org

Patcher’s PowerTools plug-in, http://www.mpibpc.gwdg.de/abtei-lungen/140/software/index.html (WaveMetrics)

ENCODE, http://genome.ucsc.edu/ENCODE

LDlink, https://dceg.cancer.gov/tools/analysis/ldlink

IMPC, http://www.mousephenotype.org

Clinical Trials, https://clinicaltrials.gov/

Cyflogic, http://www.cyflogic.com

ImageJ, https://imagej.nih.gov/ij/

OMIM, http://www.omim.org

RefSeq, https://www.ncbi.nlm.nih.gov/refseq/

UCSC Genome Browser, http://genome.ucsc.edu

UniProt, http://www.uniprot.org

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FIGURE LEGENDS

Figure 1. Genome-wide Linkage and Transcriptome Analysis Uncovered NCALD as Candidate Modifier of SMA.

(A) Pedigree of the Utah family: haplotype analysis of microsatellite markers in the 5q13 SMA region and *SMN1* and *SMN2* copies are indicated. Black filled symbols: SMA-affected individuals, grey filled symbols: asymptomatic *SMN1*-deleted individuals and symbols with a dot: SMA carriers. Quantification of *PLS3* expression in LBs was done according to[24]. Note weak *PLS3* have no impact on SMA phenotype[24].

(B) Genome-wide linkage analysis identified eight regions with positive LOD scores. Open arrow marks 8q22.3 region containing *NCALD*.

(C) Verification of microarray results (Table S2) of *NCALD* RNA and protein in lymphoblastoid (LB) cells (NCALD levels are relative to NCALD in SMA patients of Utah family (set to 100%)). *NCALD* is represented by two independent probes on the expression array, showing a 4-to-5 fold downregulation in the asymptomatic group *versus* familial type 1 SMA or an independent type 3 SMA group. Three independent experiments including all 17 cell lines (asymptomatic, N = 5; symptomatic, N = 2; independent SMA-III, N = 10) were performed. * $P \leq 0.05$.

(D) Expression analysis of *NCALD* RNA and proteins in fibroblasts (FB) derived from the Utah family (asymptomatic, N = 5; symptomatic, N = 2). Three independent experiments including all seven cell lines were performed. ** $P \leq 0.01$; *** $P \leq 0.001$.

Figure 2. NCALD Downregulation Restores Neurite Outgrowth Defect in SMN-deficient Neuronal Cells.

(A) Western blot of NSC34 cells treated with 1μM retinoic acid (RA) for 0-120h as a model of MN differentiation and maturation (n = 3 independent experiments).

(B) *Ncald* siRNA-treated NSC34 cells show signs of MN differentiation (HB9-positive staining, marked with white arrows) even in absence of RA (right panel). As positive control, cells were

differentiated with RA and treated with control siRNA (middle panel). Negative control was treated only with control siRNA (left panel). Scale bar, 100 µm.

(C) Primary MNs from SMA or HET murine embryos were fixed at 8 DIV and stained with anti-neurofilament M (anti NF-M). Quantitative analysis of axon length of MNs. SMA: N = 7, HET: N = 6, n = 100 per measurement; *** P ≤0.001; dashed line = mean; straight line = median. Scale bar, 100 µm.

Figure 3. Ncald Reduction Corrects the Phenotype in Smn-deficient Zebrafish

(A) First 10 motor axons posterior to the yolk globule of 34 hpf zebrafish embryos injected with respective morpholinos (MO). White arrows mark truncated motor axons. Arrowheads mark extensive branching in *ncald* or *smn*+*ncald* morphants; green = Znp1 staining, for motor axons. Scale bar, 100 µm.

(B) Western blot of lysates of zebrafish embryos injected with indicated MO.

(C) Quantification of motor axon phenotype. Dashed lines mark the rescue of the truncation phenotype (**P≤ 0.01). *smn*+*ncald* and *ncald* morphants showed increased branching. n >500 motor axons per MO injection.

(D) TEM images of NMJs of 48 hpf zebrafish embryos injected with respective MO. White arrows mark synaptic clefts including basal lamina. M = muscle fiber, T = nerve terminal. Scale bar, 100 nm.

(E) Quantification of synaptic cleft width of MO-injected 48 hpf fish (n = 15 per treatment). **P ≤0.01, dashed line=mean; straight line=median.

(F, G) Whole-cell current clamp recordings EPPs (F) and quantification (G) of mean EPP frequencies in ventral fast muscle cells of control (n = 12), *smn* (n = 10), *ncald* (n = 11) and *smn+ncald* (n = 12) morphants under control conditions or NMDA induction. White bar parts reflect the mEPP frequencies, grey bar parts reflect the frequency of the TTX-sensitive large EPPs. **P ≤0.01; ***P ≤0.001.

Figure 4. Heterozygous *Ncald* KO Improves Axonal Outgrowth, Proprioceptive Input and NMJ Size in Severe SMA Mice

(A) Western blot and quantification of NCALD and ACTB (loading control) in spinal cord and hippocampus of P10-old wt and *Ncald*$^{ko/wt}$ mice. *P ≤ 0.05.

(B) Representative images and quantification of NMJ area [µm^2] in TVA muscle from P10-old mice stained with antibodies against NF-M and SV2 (green, for presynaptic terminals) and Bungarotoxin (magenta, for postsynapse). NMJ area was analyzed with ImageJ software (N = 3, n =100-120 NMJs/mouse). ***P ≤ 0.001. Scale bar, 10 µm.

(C) Representative images and quantification of proprioceptive inputs (VGLUT1, green) on MN soma (CHAT, magenta) in lumbar spinal cord sections from P10-old mice. Mean input number within 5 µm of MN soma was analyzed (N = 3, n = 100-120 MNs/mouse). ***P ≤ 0.001. Scale bar, 25 µm. Note, colour code for genotypes is identical to panel D.

(D) Representative merged images of 6 DIV MNs isolated from E13.5 embryos and stained with DAPI (blue, for DNA) and antibodies against HB9 (green, for MN) and Tau (red, for axon). The longest axon and axonal branches were quantified with ImageJ (N = 3-5, n = 20-40 axons per mouse). Scale bar, 25 µm. Each box plot covers values from 25-75% with line at median and dotted outliers at <5% and >95% CI. For each experiment, image analysis was double-blinded. n.s. non-significant; *P ≤ 0.05; **P ≤ 0.01; ***P ≤ 0.001.

Figure 5. NCALD Reduction Improves Motoric Function, NMJ Size, and NMJ Architecture in SMA+ASO Mice

(A) Breeding scheme to produce mixed$_{50}$ SMA and HET mice. All mixed$_{50}$ offspring were injected with 30 µg SMN-ASO at P1.

(B) Kaplan-Meier curves of uninjected mixed$_{50}$ mice show no differences in survival between SMA (17 days, N = 7) and SMA-*Ncald*$^{ko/wt}$ (16.5 days, N = 12). Injection of 30 µg SMN-ASO on

P1 increases survival to >180 days for both SMA+ASO (N = 10) and SMA-*Ncald*$^{ko/wt}$+ASO (N = 12) mice.

(C) Righting reflex test shows improvement in SMA-*Ncald*$^{ko/wt}$+ASO, but not SMA+ASO mice during P2-P6 (n ≥12 per genotype). Error bars represent SEM. n.s. non-significant, **P ≤ 0.01, ***P ≤ 0.001.

(D) Grip strength test performance at P73 reveals enhanced strength for SMA-*Ncald*$^{ko/wt}$+ASO mice compared to SMA+ASO mice (N ≥12 per genotype). Error bars indicate SEM. *P ≤0.05, **P ≤ 0.01, ***P ≤ 0.001.

(E) Representative images of NMJs of ASO-treated mixed$_{50}$ mice at P21 stained with the antibody against NF-M (green, for presynaptic terminal) and Bungarotoxin (magenta, for postsynaptic terminal). Scale bar, 20μm. Box plot shows quantification of NMJ area in μm^2 in TVA muscle which was analyzed and represented as in Figure 4

(F) Bar graph shows percentage of immature NMJs in TVA muscle (mean ± SD). N = 3 mice per genotype; n = 60-100 NMJs per mouse. n.s. non-significant, *P ≤0.05, **P ≤0.01, ***P ≤ 0.001.

Figure 6. Interconnection Between SMN, NCALD, Voltage-dependent Ca^{2+} Influx, Endocytosis and SMA

(A) Measurement of *I-V* relations of Ca^{2+} tail currents in differentiated NSC34 cells treated with respective siRNAs and depolarized for 5 ms to 60 mV, in 5 mV increments, at holding potential -80 mV. Currents were not different between wildtype (N = 7), control siRNA (n = 33) and *Ncald* KD (n = 13) and were significantly reduced upon *Smn* KD (n = 15) and *Smn*+*Ncald* KD (n = 12) at current pulses above -35 mV. *P ≤ 0.05; **P ≤ 0.01; ***P ≤ 0.001.

(B) Western blot of co-immunoprecipitation experiment. NSC34 cells were transiently transfected with FLAG-His-NCALD or control vector. Co-immunoprecipitations with FLAG-M2 affinity beads were performed in the presence or absence of Ca^{2+}. NCALD interacts with clathrin only in the absence of Ca^{2+} (addition of EGTA to the cell lysate) but not in the presence.

Note the positive clathrin band in the test-CoIP (fourth lane) in the absence but not in the presence of Ca^{2+} (last lane). .

(C) Quantification of endocytosis by FITC-dextran uptake in fibroblasts from SMA (N = 10), controls (N = 3) and asymptomatic individuals (N = 5); n = 50 per cell line and time point. Mean ±SD.*P≤ 0.05, **P ≤ 0.01.

(D) Quantification of FM1-43 intensity at presynaptic terminals in TVA muscles under low frequency stimulation (5 Hz, 1s). N = 3 per genotype, n ≈100 per mouse. Mean ±SEM. n.s. non-significant; ***P ≤ 0.001.

(E) Quantification of MN axon phenotype of zebrafish embryos treated with sub-phenotypical doses of *smn* MO (2 ng), *ncald* MO (2 ng) and the endocytosis inhibitors Pitstop2 and Dynasore, respectively. Dashed lines highlight the synergistic effect of *smn* MO and Pitstop2 and the effect of Dynasore on axon truncation. Additional *ncald* MO injection ameliorates the truncation defect. ***P ≤ 0.001. Motor axons per treatment: Pitstop2: n ≥100, Dynasore: n ≥150.

Figure 7. NCALD Acts as a Ca^{2+}-dependent Regulator of Endocytosis in Synaptic Vesicle Recycling

Diagrammatic presentation of the mode of action of NCALD in synaptic vesicle recycling in normal, SMA, and asymptomatic pre-synapse of neuronal cells. From left to right: 1) following neurotransmitter release, clathrin binds to empty vesicle membrane causing membrane bending and vesicle formation. High concentration of local Ca^{2+} which is present after vesicle release[96] causes NCALD conformational change and thereby a release of clathrin so that it can perform its function. NCALD may fine-tune recycling speed and help to coordinate proper clathrin coating. 2) In SMA, voltage dependent Ca^{2+} influx is reduced, decreasing NCALD-clathrin dissociation, thus inhibiting clathrin coating of vesicles. In our model NCALD regulates (increases) the Ca^{2+} dependence of clathrin function. 3) When NCALD level is reduced the Ca^{2+} dependence is reduced too and even at relative low intracellular Ca^{2+} levels clathrin can mediate endocytosis.

Figure1

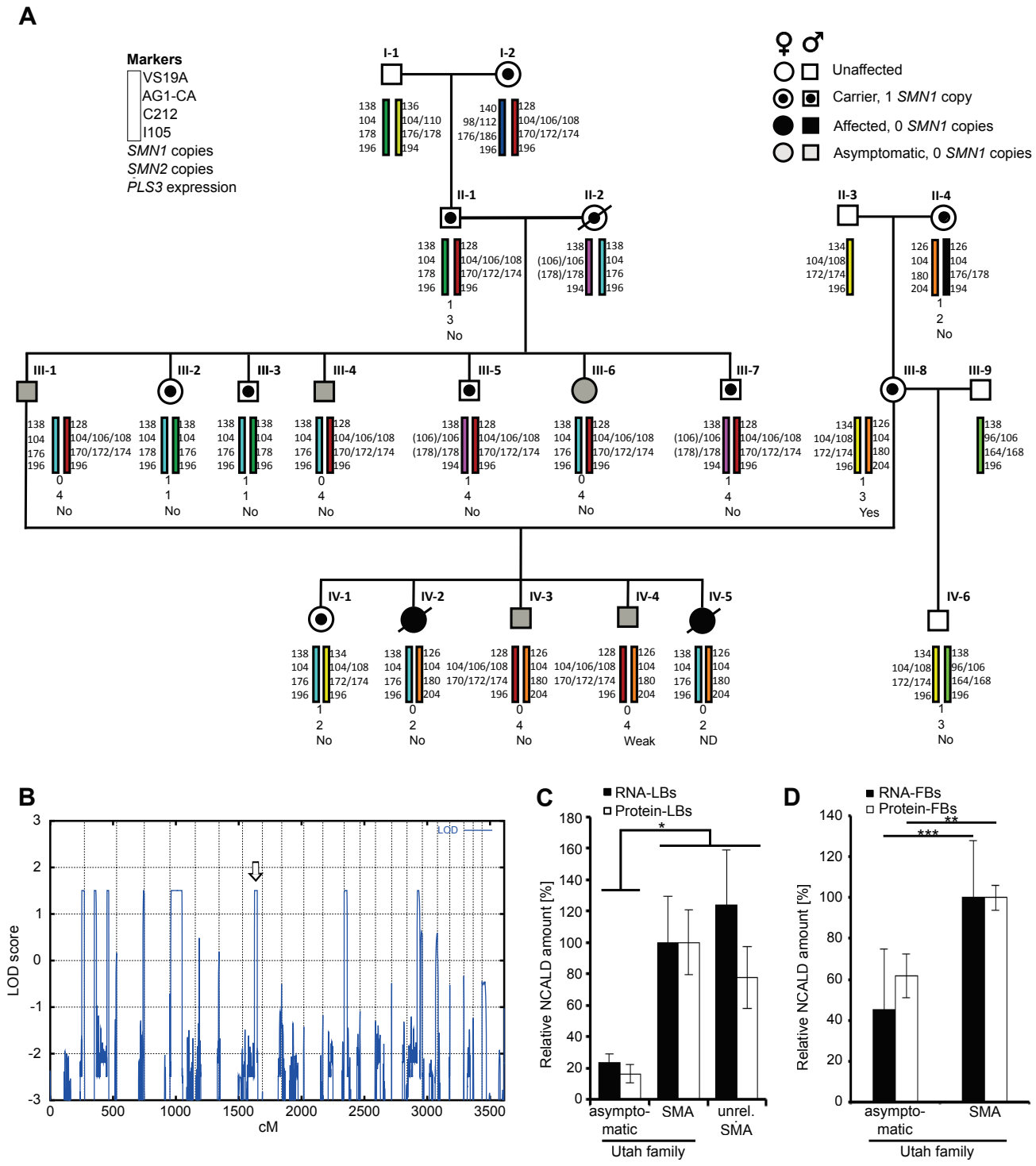

A
Markers
VS19A
AG1-CA
C212
I105
SMN1 copies
SMN2 copies
PLS3 expression
Unaffected
Carrier, 1 SMN1 copy
Affected, 0 SMN1 copies
Asymptomatic, 0 SMN1 copies
I-1
I-2
II-1
II-2
II-3
II-4
III-1
III-2
III-3
III-4
III-5
III-6
III-7
III-8
III-9
IV-1
IV-2
IV-3
IV-4
IV-5
IV-6
No
Yes
Weak
ND
B
LOD score
cM
C
RNA-LBs
Protein-LBs
Relative NCALD amount [%]
asympto-matic
SMA
unrel. SMA
Utah family
D
RNA-FBs
Protein-FBs
Relative NCALD amount [%]
asympto-matic
SMA
Utah family

Figure2

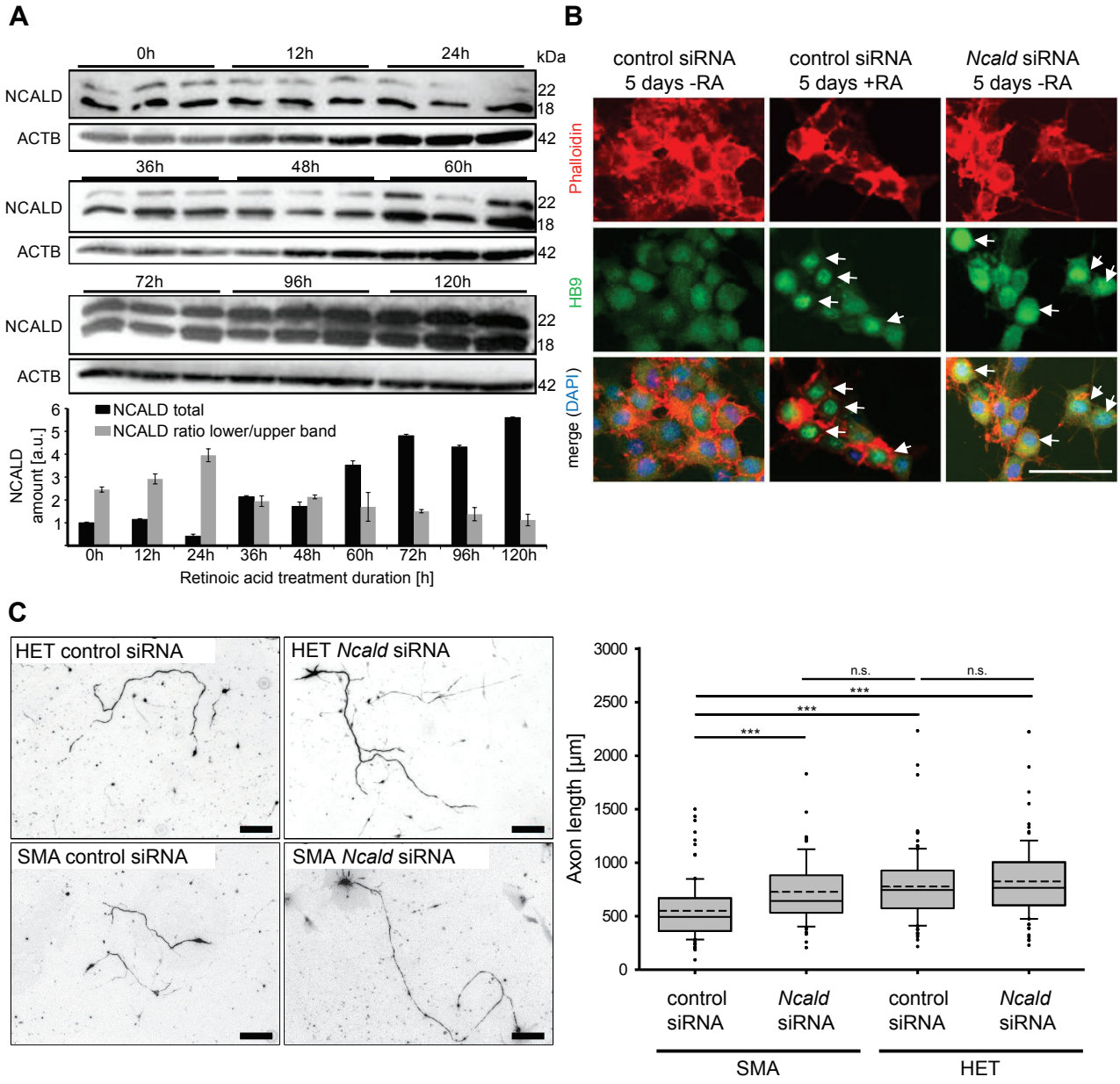

A
0h
12h
24h
kDa
NCALD
ACTB
22
18
42
36h
48h
60h
72h
96h
120h
NCALD total
NCALD ratio lower/upper band
NCALD amount [a.u.]
Retinoic acid treatment duration [h]
B
control siRNA 5 days -RA
control siRNA 5 days +RA
Ncald siRNA 5 days -RA
Phalloidin
HB9
merge (DAPI)
C
HET control siRNA
HET Ncald siRNA
SMA control siRNA
SMA Ncald siRNA
Axon length [µm]
n.s.
***
control siRNA
Ncald siRNA
SMA
HET

Figure3

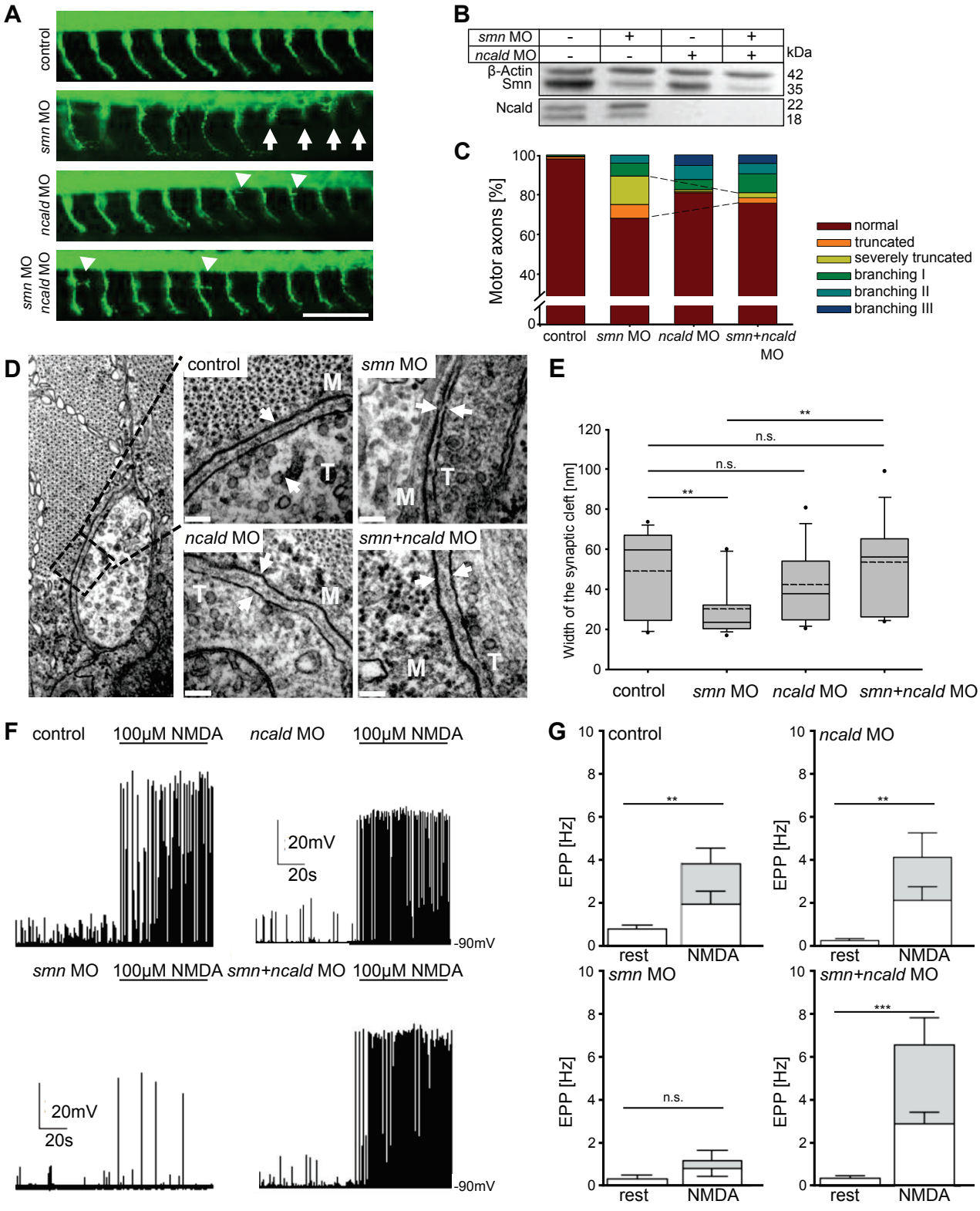

A
control
smn MO
ncald MO
smn MO
ncald MO
B
smn MO - + - +
ncald MO - - + +
kDa
β-Actin
Smn
42
35
Ncald
22
18
C
Motor axons [%]
100
80
60
40
0
control
smn MO
ncald MO
smn+ncald MO
normal
truncated
severely truncated
branching I
branching II
branching III
D
control
smn MO
ncald MO
smn+ncald MO
M
T
E
Width of the synaptic cleft [nm]
120
100
80
60
40
20
0
**
n.s.
n.s.
**
control
smn MO
ncald MO
smn+ncald MO
F
control
100µM NMDA
ncald MO
100µM NMDA
20mV
20s
-90mV
smn MO
100µM NMDA
smn+ncald MO
100µM NMDA
20mV
20s
-90mV
G
control
ncald MO
smn MO
smn+ncald MO
EPP [Hz]
10
8
6
4
2
0
**
**
n.s.
***
rest
NMDA

Figure4

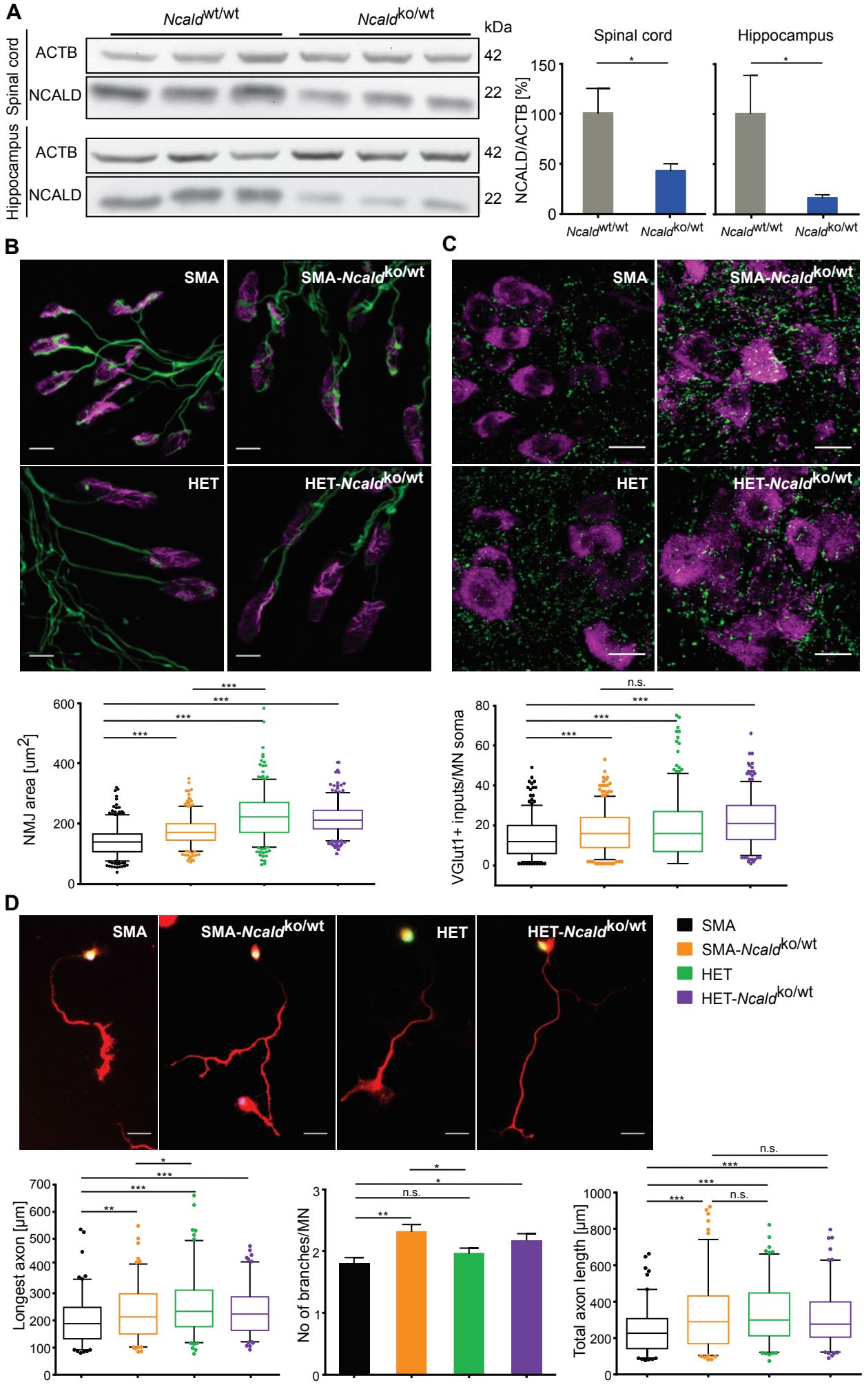

A
Ncald wt/wt
Ncald ko/wt
kDa
Spinal cord
ACTB
NCALD
Hippocampus
ACTB
NCALD
42
22
42
22
Spinal cord
Hippocampus
NCALD/ACTB [%]
150
100
50
0
Ncald wt/wt
Ncald ko/wt
Ncald wt/wt
Ncald ko/wt
B
SMA
SMA-Ncald ko/wt
HET
HET-Ncald ko/wt
C
SMA
SMA-Ncald ko/wt
HET
HET-Ncald ko/wt
NMJ area [um2]
600
400
200
0
VGlut1+ inputs/MN soma
80
60
40
20
0
n.s.
D
SMA
SMA-Ncald ko/wt
HET
HET-Ncald ko/wt
SMA
SMA-Ncald ko/wt
HET
HET-Ncald ko/wt
Longest axon [µm]
700
600
500
400
300
200
100
0
No of branches/MN
3
2
1
0
n.s.
Total axon length [µm]
1000
800
600
400
200
0
n.s.
n.s.

Figure5

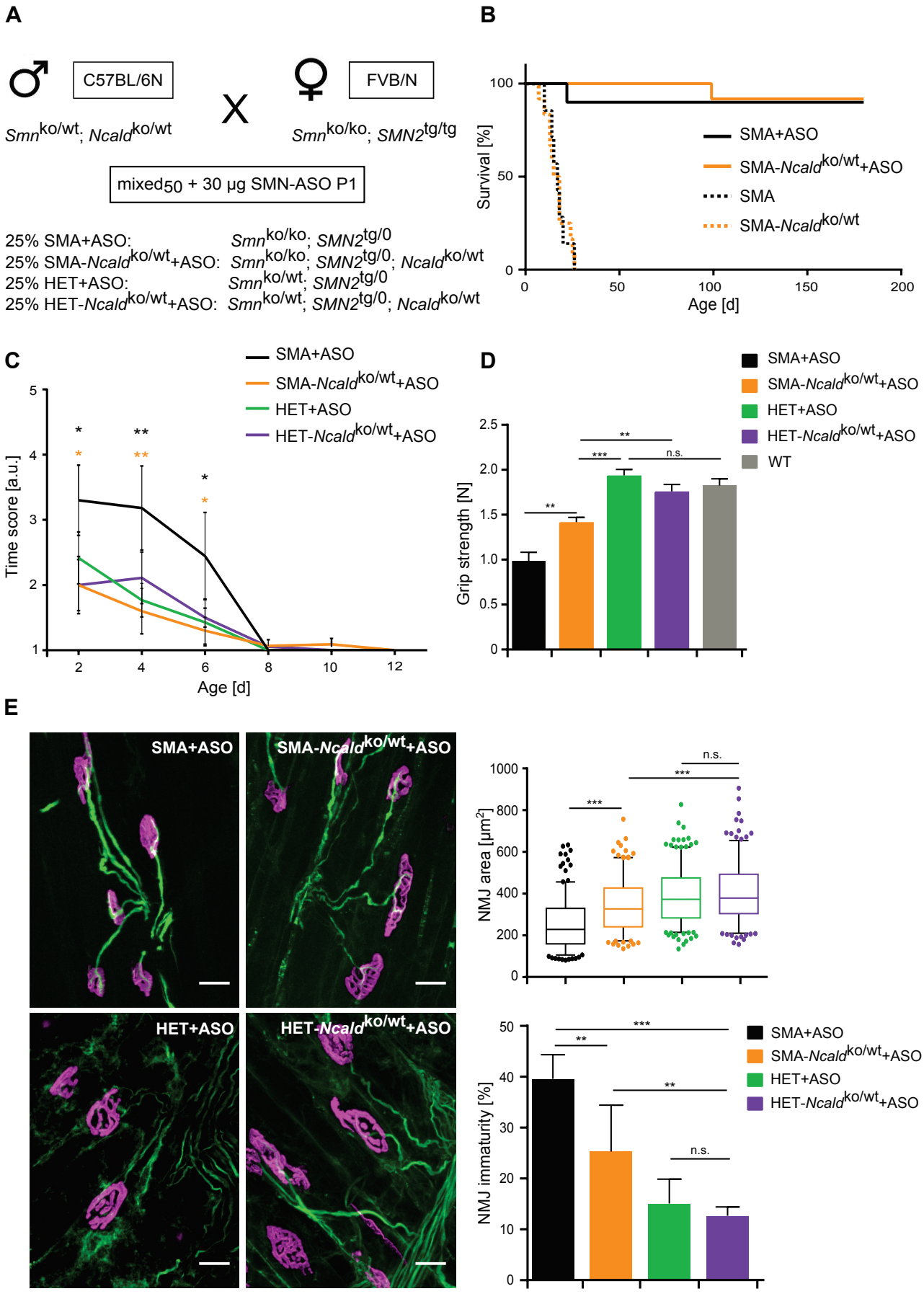

A
C57BL/6N
FVB/N
Smn^ko/wt; Ncald^ko/wt
Smn^ko/ko; SMN2^tg/tg
mixed50 + 30 µg SMN-ASO P1
25% SMA+ASO: Smn^ko/ko; SMN2^tg/0
25% SMA-Ncald^ko/wt+ASO: Smn^ko/ko; SMN2^tg/0; Ncald^ko/wt
25% HET+ASO: Smn^ko/wt; SMN2^tg/0
25% HET-Ncald^ko/wt+ASO: Smn^ko/wt; SMN2^tg/0; Ncald^ko/wt
B
Survival [%]
Age [d]
SMA+ASO
SMA-Ncald^ko/wt+ASO
SMA
SMA-Ncald^ko/wt
C
Time score [a.u.]
Age [d]
SMA+ASO
SMA-Ncald^ko/wt+ASO
HET+ASO
HET-Ncald^ko/wt+ASO
D
Grip strength [N]
SMA+ASO
SMA-Ncald^ko/wt+ASO
HET+ASO
HET-Ncald^ko/wt+ASO
WT
n.s.
E
SMA+ASO
SMA-Ncald^ko/wt+ASO
HET+ASO
HET-Ncald^ko/wt+ASO
NMJ area [µm²]
NMJ immaturity [%]
n.s.

Figure6

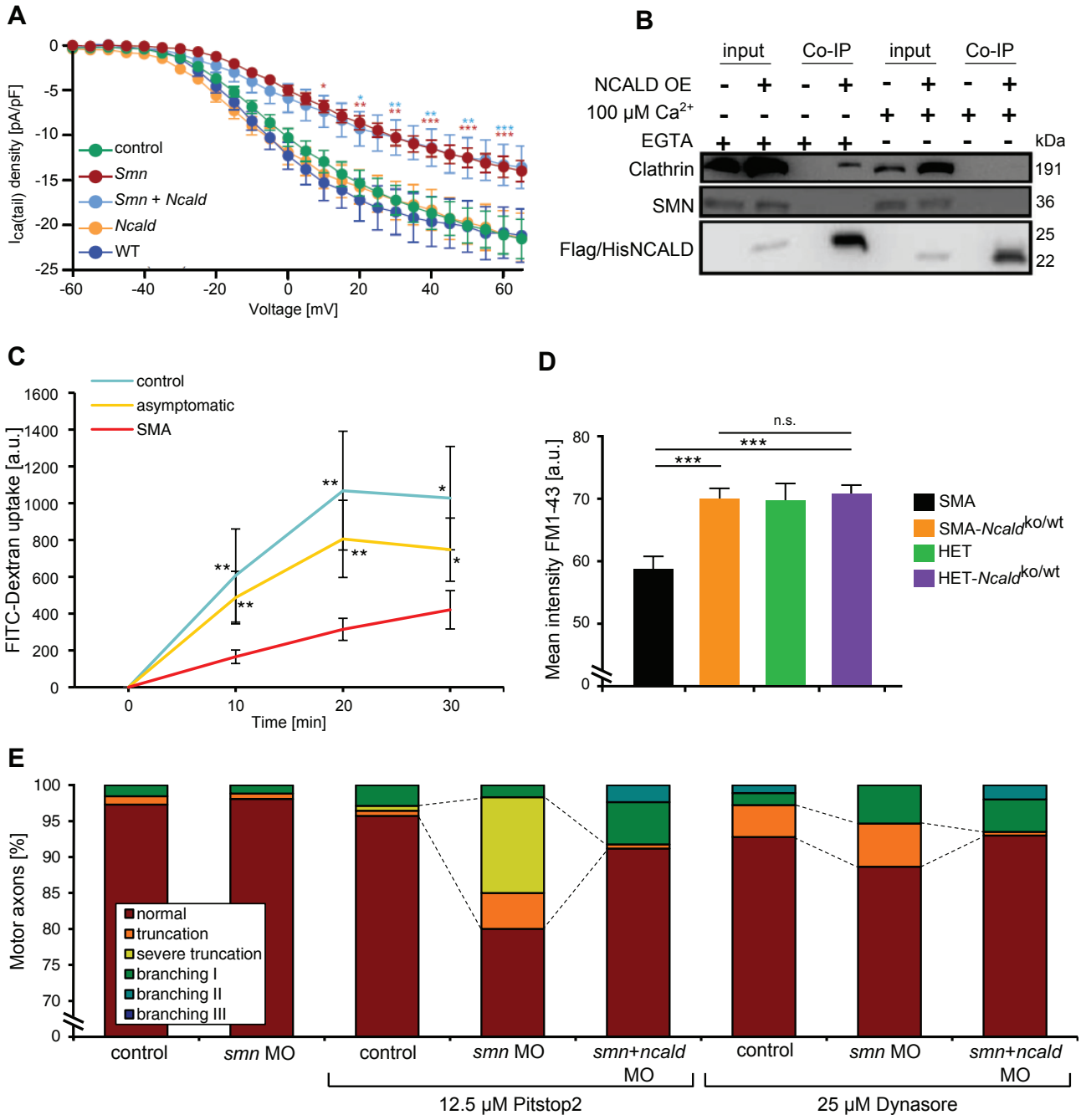
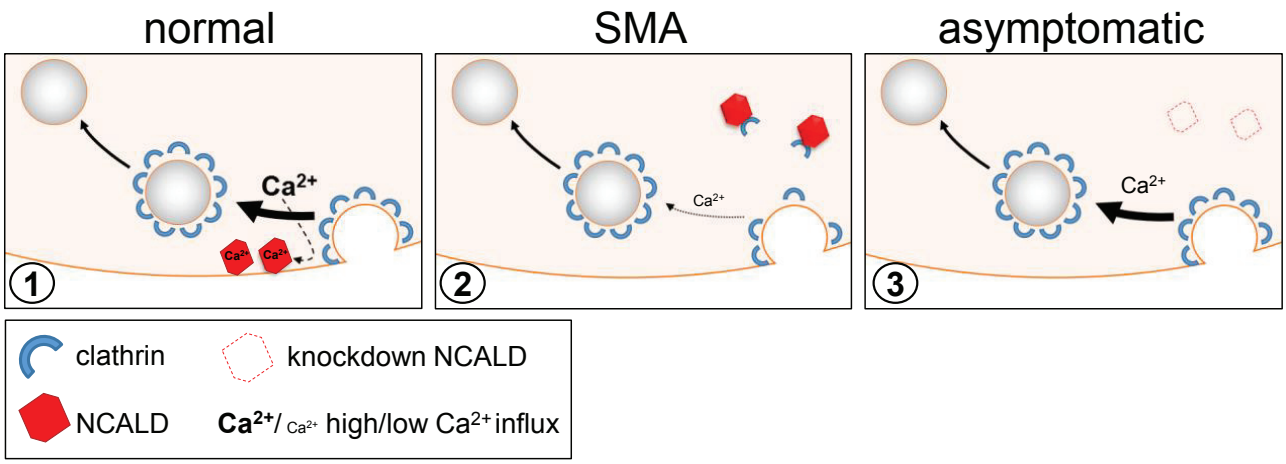
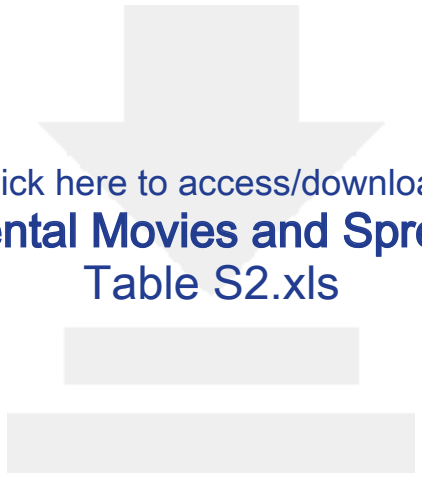

A
control
Smn
Smn + Ncald
Ncald
WT
Voltage [mV]
B
input
Co-IP
input
Co-IP
NCALD OE
100 µM Ca2+
EGTA
kDa
Clathrin
SMN
Flag/HisNCALD
191
36
25
22
C
control
asymptomatic
SMA
FITC-Dextran uptake [a.u.]
Time [min]
D
Mean intensity FM1-43 [a.u.]
n.s.
SMA
SMA-Ncaldko/wt
HET
HET-Ncaldko/wt
E
Motor axons [%]
normal
truncation
severe truncation
branching I
branching II
branching III
control
smn MO
control
smn MO
smn+ncald MO
control
smn MO
smn+ncald MO
12.5 µM Pitstop2
25 µM Dynasore

Figure7


normal
SMA
asymptomatic
Ca2+
Ca2+
Ca2+
Ca2+
1
2
3
clathrin
knockdown NCALD
NCALD
Ca2+/ Ca2+ high/low Ca2+ influx

Supplemental Text and Figures

Table S2



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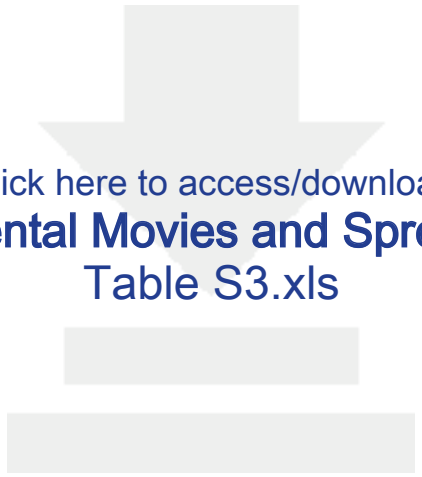
Supplemental Movies and Spreadsheets

Table S2.xls

Table S3



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Supplemental Movies and Spreadsheets

Table S3.xls