



Alterations in glutamatergic signaling contribute to the decline of circadian photoentrainment in aged mice



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ABSTRACT

Robust physiological circadian rhythms form an integral part of well-being. The aging process has been found to negatively impact systems that drive circadian physiology, typically manifesting as symptoms associated with abnormal/disrupted sleeping patterns. Here, we investigated the age-related decline in light-driven circadian entrainment in male C57BL/6J mice. We compared light-driven resetting of circadian behavioral activity in young (1–2 months) and old (14–18 months) mice and explored alterations in the glutamatergic pathway at the level of the circadian pacemaker, the suprachiasmatic nucleus (SCN). Aged animals showed a significant reduction in sensitivity to behavioral phase resetting by light. We show that this change was through alterations in N-Methyl-D-aspartate (NMDA) signaling at the SCN, where NMDA, a glutamatergic agonist, was less potent in inducing clock resetting. Finally, we show that this shift in NMDA sensitivity was through the reduced SCN expression of this receptor's NR2B subunit. Only in young animals did an NR2B antagonist attenuate behavioral resetting. These results can help target treatments that aim to improve both physiological and behavioral circadian entrainment in aged populations.

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1. Introduction

Aging is commonly associated with a loss in expression of circadian (daily) rhythms, which can lead to problems in sleep, cognition, and social function. To assist in prevention or amelioration of these age-related losses, we need to better understand the underlying causes. The circadian system in mammals is well characterized. The central pacemaker, the suprachiasmatic nucleus (SCN) of the hypothalamus, generates multiple rhythmic outputs that entrain circadian clocks in tissues throughout the body (Morin and Allen, 2006; Reppert and Weaver, 2002). Cells in the SCN are entrained to the environmental light-dark cycle via a specialized input pathway from the retina (Lucas et al., 2012). Aging has the potential of influencing all aspects of the circadian entraining circuitry, from the eye through to SCN input and ultimately output signaling.

The eye is known to undergo structural changes with age, which can also impact function (Lin et al., 2016). Light information is decoded by retinal photoreceptors of different types: rods, cones, and a subset of retinal ganglion cells expressing the melanopsin photopigment (Lucas, 2003). These cells provide visual cues of our surroundings and encode the irradiance of varying levels of ambient light. It is this latter physiological attribute that dictates many of the nonvisual light-driven processes, such as circadian entrainment, pupil size, pineal melatonin production, and sleep propensity (Lucas et al., 2012). With healthy aging, both visual acuity and color contrast show gradual deterioration over time. However, progressive, and often relatively rapid, declines in the visual processing are often due to age-associated health disorders such as macular degeneration and glaucoma or more centrally through various forms of dementia (Maynard et al., 2017; Wulff, 2015).

Changes in the SCN with age have already been reported in laboratory animals such as mice, rats, and hamsters. These include altered expression of primary neuropeptides typically responsible for SCN cell orchestration, decreases in glucose uptake, and declines in oscillatory activity of SCN neurons (Biello, 2009;

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Duncan et al., 2001; Kawakami et al., 1997; Krajnak et al., 1998; Madeira et al., 1995; Satinoff et al., 1993; Wise et al., 1988). SCN output function appears to be compromised with age, given that multiple studies report dampened amplitude of the circadian rhythm in neuronal spontaneous cell firing (Farajnia et al., 2012; Leise et al., 2013; Nakamura et al., 2011). We have previously shown that voluntary exercise, a nonphotic stimulus, appears to remain an effective cue in aged mice. We have demonstrated that SCN firing rate, circadian gene *PER2::LUC* expression, and phase resetting to light can all respond to nonphotic input in aged mice (Leise et al., 2013). In addition, a lack of exercise can negatively impact locomotor scale invariance in aged mice, providing further evidence for the importance of behavioral intervention in healthy aging (Gu et al., 2015). On the other hand, it is unclear if photic responses of SCN cells are impaired with age.

Light-driven SCN responses are mediated by the excitatory neurotransmitter glutamate. Shifts in SCN cell firing rhythms on application of glutamate, *in vitro*, mimic those of light *in vivo* (Ebling, 1996). In addition, the action of glutamate, in part, has been attributed to the N-Methyl-D-aspartate (NMDA) receptor, where light-induced behavioral shifts were blocked by an NMDA receptor antagonist *in vivo* (Colwell et al., 1990). Furthermore, direct application of the glutamatergic agonist NMDA to the SCN results in light-like behavioral resetting (Ding et al., 1994).

The NMDA receptor is a ligand-gated ion channel that consists of 4 membrane-bound subunits, 2 NR1, and one or more NR2 (NR2A, NR2B, NR2C, NR2D, NR3A, NR3B) subunits (Cull-Candy et al., 2001; Flores-Soto et al., 2012; Kumar, 2015; McBain and Mayer, 1994). The NR2 subunit defines the pharmacological characteristics of the receptor. The NR2B subunit has been shown to be important in the mediation of light signals to the circadian clock during the early and late night (Wang et al., 2008). Inhibition of NR2B-expressing receptors by the selective antagonist ifenprodil attenuated both phase delays and advances to light. Overall declines in the expression of NMDA receptors have been shown in a range of aged mammals from humans to rodents (Magnusson, 2000; Piggott et al., 1992). In particular, a decrease in NR2B expression has been found in most cortical regions and dentate granule cells of aged mice (Magnusson, 2000).

Here, we investigate the impact of light sensitivity and NMDA signaling on circadian resetting in aged mice. Our studies investigate the impact at both the level of the eye and the SCN. We hypothesize that circadian deficits in senescence are the result of changes to the photic input pathway driven by alterations in NMDA signaling within the SCN.

2. Methods

2.1. Animals

Male C57BL/6J mice (purchased from Charles River [Kent, UK {SMB and GSL}] or Jackson Laboratories [MA, USA {MEH}]) and bred in-house) were housed in groups of 1–4 before experimentation and then individually housed, with food and water provided *ad libitum*. Young animals were defined as mice aged between 1–2 months; aged mice were defined as animals aged between 14–18 months. Environmental room lighting consisted of white fluorescent strips providing approximately 250–350 lux at the level of the cage. All mice were maintained under a 12:12 hours light-dark (LD) cycle for a minimum of 14 days before being assigned to an experimental group. All experimental procedures were performed with approval from the Universities of Glasgow [SMB] and Kent [GSL] Ethical Review Committees (UK) and in accordance with the UK Home Office Animals (Scientific Procedures) Act 1986. All experimental work with animals at Smith College (USA [MEH]) was

approved by the Institutional Animal Care and Use Committee, and the work was conducted in an Association for Assessment and Accreditation of Laboratory Animal Care (AAALAC)-accredited animal facility.

2.2. Surgery

Mice (University of Glasgow, UK) were anesthetized with a ketamine-xylazine mix (50 mg/Kg, 20 mg/Kg, respectively) administered intraperitoneally (*i.p.*) on the day of surgery. Guide cannulas were stereotaxically aimed at the SCN (coordinates relative to bregma: anterior-posterior (AP) –0.4 mm, lateral 0 mm, dorsal-ventral (DV) –4.7 mm) and fixed to the skull with mounting screws and dental cement. Mice were left to recover for 14 days under a 12:12 LD cycle before being placed in cages with running wheels.

Cannula placements were identified by histological and/or functional assessment. Functional cannula placements were determined by an initial microinjection of Neuropeptide Y (NPY) (Calbiochem, UK) at circadian time (CT) 6 (200 nL; 1 ng/nL). Mice that showed functional evidence of placement by shifts of at least 110 minutes were included in further cannula tests.

2.2.1. Histology

Animals were killed using an overdose of sodium pentobarbital (approximately 160 mg/kg, *i.p.*) and given an intracerebral injection of India ink (200 nL) with the same length of injector used in the experiment. They were then perfused transcardially with 0.9% saline and 10% formaldehyde. The brains were postfixed in 10% formalin followed by 30% sucrose. Frontal sections (40 μ m) were cut using a cryostat. Slices containing the SCN were mounted on Polysine microslides and stained for Nissl substance with Cresyl Violet. The distance from the injection site to the margin of the SCN was measured along the anterior-posterior, dorsal-ventral, and lateral axes. The greatest of the three measurements was taken as the distance from the SCN. No data from animals with placements more than 400 μ m from the margin of the SCN were included in analyses.

2.3. Circadian photoentrainment

Phase shifting experiments (Universities of Kent and Glasgow, UK) were performed using an Aschoff type I protocol. Animals were individually housed and placed under constant conditions of darkness (21 ± 2 °C) 10 days before experimental treatment. Cages were fitted with running wheels, and wheel revolutions were recorded in 1-minute bins and analyzed using ClockLab (Actimetrics, IL, USA). Under dim red light, groups of young ($n = 14$) and aged ($n = 14$) mice were removed from their cages and exposed to a 15-minute white fluorescent light (30 lux or 300 lux) at CT 14 (2 hours after activity onset).

Phase shifts to the glutamatergic agonist, NMDA (Sigma, Poole, UK), were assessed by central injections of NMDA (200 nL, 10 mM in artificial cerebral spinal fluid [aCSF]) at CT 14 in both young ($n = 11$) and aged ($n = 11$) animals. Vehicle controls consisted of 200 nL of aCSF (aCSF [pH 7.4]: 125.2 mM NaCl, 3.8 mM KCl, 1.2 mM KH_2PO_4 , 1.8 mM CaCl_2 , 1 mM MgSO_4 , 24.8 mM NaHCO_3 , 10 mM D-Glucose). Finally, to investigate the role of the NR2B receptor subunit in photic resetting, both groups of young ($n = 14$) and old ($n = 14$) mice were exposed to a subsaturating white light (150 lux) at CT 14, preceded by central administration of either the NR2B antagonist, ifenprodil (200 nL, 6.1 μ M in 10% dimethylsulfoxide, [Sigma UK], or a 10% dimethylsulfoxide (200 nL) vehicle control at CT 13.5.

Data were analyzed blind to condition by extrapolation lines eye-fitted through the onset of 7 days of wheel activity before the light pulse. Postpulse regression lines were fitted using onsets from

7 days of activity of the 10 days recorded, as the first 3 days after the light pulse were excluded as transients. The difference between the extrapolation lines, on the day of the stimulus, was measured to calculate behavioral phase shifts.

2.4. Pupillometry

Pupillometry (University of Kent) was conducted as previously described (Lucas, 2003) on unanesthetized young ($n = 8$) and aged ($n = 8$) mice. Animals were stably entrained to a 12:12 hours LD cycle (white fluorescent source, 350 lux), and recordings were restricted to between 4 and 7 hours after lights on (Zeitgeber time [ZT] 4–7). All experiments were preceded by 1 hour of dark adaptation. Pupillary responses were elicited with Ganzfeld light stimuli (Xe arc source, filtered with neutral density filters) applied to one eye, previously dilated with 0.1% atropine allowing consensual pupil constriction to be recorded with a CCD camera. Ten seconds of darkness separated pretreatment and test stimuli. Pupil area was measured using ImageJ (National Institutes of Health (NIH), USA) (Schneider et al., 2012) analysis software and expressed relative to its size in the 3 seconds before light onset. As an exclusion criterion, animals presenting with cataracts (detected under infrared light) would not be included in the analysis. In the sampling population used in this study, no animals exhibited signs of cataracts.

2.5. Electrophysiology

Young ($n = 6$) and old ($n = 7$), adult, male C57BL/6J mice (University of Glasgow) were housed in LD 12:12. ZT was defined as ZT 12 being the projected time of lights off in the animal room. Mice were administered an overdose of halothane anesthesia and decapitated during the phases when this manipulation does not induce phase shifts (Gillette, 1986), between ZT 2 and ZT 5. Hypothalamic slices (500 μm) containing the SCN were placed in a gas-fluid interface slice chamber (Medical Systems BSC with Haas top) and continuously bathed (1 mL/min) in aCSF. aCSF (pH 7.4) was supplemented with an antibiotic (gentamicin, 0.05 gm/l) and a fungicide (amphotericin, 2 mg/L) and maintained at 34.5 °C. Warm, humidified 95% oxygen: 5% carbon dioxide was continuously provided.

Extracellular single-unit activity of SCN cells was detected with glass micropipette electrodes filled with aCSF, advanced through the slice using a hydraulic microdrive. The electrode was placed into regions of the SCN at random, alternating between the left and right SCN. The signal was fed into an amplifier for further amplification and filtering and was continuously monitored by an oscilloscope and audio monitor. Firing rate and interspike interval data were analyzed using Spike 2 (Cambridge Electronic Design, Cambridge, UK) data acquisition software and a customized program for calculation of descriptive statistics. The average spontaneous firing rate and the ZT for each single unit encountered was recorded for 4–5 minutes by an experimenter blind to all treatments.

NMDA (Sigma Aldrich, Dorset, UK) was dissolved in aCSF (Biello et al., 1997) and applied at a concentration of 10 μM as a 200-nL microdrop to the SCN area of the slice. Microdrops were administered using a Hamilton 1- μL syringe on the same day as slice preparation at ZT 14, with ZT 12 being defined as the animal's activity onset in vivo before SCN removal. Drugs were warmed to 34.5 °C. Recordings were performed for approximately 20 hours during ZT 0–20 of the second 24 hours in vitro. Slices with less than 4 cells recorded during any 1-hour period were not included in the analysis.

Initially, the average firing rate of each cell recorded from one slice was plotted against the ZT of the recording. Slices without

significant differences across firing rate data grouped into 1 hour (ZT) bins ($p < 0.05$; analysis of variance [ANOVA]) were not used for further analysis. If there were significant differences, data were smoothed by 1-hour running means with a 15-minute lag. The time corresponding to the maximum of the smoothed data was used as the time of the peak firing. Phase shifts were measured relative to the average time of peak firing of the age-appropriate control slices treated with aCSF at ZT 14.

2.6. Real-time polymerase chain reaction

Young and aged mice (University of Kent and Smith College) entrained under a 12:12 LD cycle were sacrificed by cervical dislocation at ZT 6 (6 hours after lights on, young $n = 7$, old $n = 7$) and ZT 18 (6 hours after lights off, young $n = 7$, old $n = 7$) to give midday and midnight time points, respectively. Bendova et al. (2012) previously demonstrated circadian variation in both mRNA and protein expression of the NR2B subunit in the rat SCN. Protein levels were highest during the night at CT 18 and lower during the subjective day. Coronal brain sections containing the SCN were collected between ZT 5.5–ZT 6.5 and between ZT 17.5–ZT 18.5 using a vibratome. The SCN was isolated from these sections using a punch tool and stored in RNAlater (Sigma Aldrich, Dorset, UK) at -80 °C until processed. Total RNA was isolated from SCN extracts using TRI Reagent (Applied Biosystems, UK); 100–500 ng total RNA was reverse-transcribed using the Transcriptor High Fidelity cDNA Synthesis Kit (Roche, UK). Twenty microliter reactions were run in triplicate in a 96-well white-colored plate containing 10 μL 2 \times SYBR Green Mix (Roche Applied Sciences, Sussex, UK), 1 μL 0.5- μM forward primer, 1 μL 0.5- μM reverse primer, 7 μL nuclease-free water, and 1- μL sample cDNA on a LightCycler 480 Real Time PCR machine (Roche Applied Sciences, Sussex, UK).

Primer sequences for real-time polymerase chain reaction (PCR) identification, as reported by Slattery et al. (2006):

NR1f:GCTGTACCTGCTGGACCGCT, NR1r:GCAGTGTAGGAAGCCAC TATGATC, NR2Af:GCTACGGGCAGACAGAGAAG, NR2Ar:GTGGTTGT CATCTGGCTCAC, NR2Bf:GCTACAACACCCAGAGAAGAG, NR2Br:GA GAGGGTCCACGCTTTCC, 18S-rRNAf:CGCCGCTAGAGGTGAAATTC, 18S-rRNAr:CGAACCTCCGACTTTCGTTCT.

Reactions were preincubated at 95 °C for 5 minutes before 55 cycles of 95 °C for 10 seconds, 60 °C for 10 seconds, and 72 °C for 10 seconds. Fluorescent detection after each cycle occurred at 82 °C. Relative quantification was determined using the 2- $\Delta\Delta\text{CT}$ method described previously by Livak and Schmittgen, 2001.

2.7. Power analysis

We have previously reported the effects of saturating and subsaturating light exposure at CT 14 on behavioral phase delays in young C57Bl/6J mice (Bonsall and Lall, 2013). A post hoc analysis showed that subsaturating light had a large effect (Cohen's $d = >4$) on behavioral phase shifts. Similarly, others have demonstrated that intracranial volume delivery of NMDA at CT 14 causes significant behavioral phase delays with a large effect size (Cohen's $d = 2$) (Mintz et al., 1999). We predicted that aged mice will show a significant but smaller effect in response to light or NMDA exposure. Using G*Power (Faul et al., 2009, 2007), a priori analysis indicated that more conservative effects of Cohen's $d = 1.4$ at $>80\%$ power would require group sizes of $n=10$ to detect significance at $\alpha = 0.05$.

A post hoc power analysis of our previous electrophysiology study showed NMDA has a large effect on both amplitude and phase shifting of SCN firing in both young (Cohen's $d = >8$) and aged (Cohen's $d = >9$) mice (Biello, 2009). A priori power analysis predicting a smaller effect size, Cohen's $d = 1.8$ at $>80\%$ power

would be sufficient to detect significant differences ($\alpha = 0.05$) with groups sizes of $n = 6$.

2.8. Statistical analysis

All results are reported as mean \pm standard error of the mean (SEM). For all experiments, statistical significance was determined using GraphPad Prism software (V.6., San Diego, CA) and defined as $p < 0.05$. All data groups were tested for, and successfully passed ($p > 0.05$), normality scoring using the D'Agostino & Pearson omnibus normality test. Behavioral phase shifts to light were analyzed using a repeated measures two-way ANOVA (light intensity \times age as factors) followed by Tukey-Kramer multiple comparisons post hoc test. Behavioral phase shifts to NMDA/Ifenprodil were analyzed using a repeated measures two-way ANOVA (treatment \times age as factors) followed by Tukey-Kramer multiple comparisons test. Pupillometry data were analyzed using curve fit analysis applying the least squares method and the extra-sum-of-squares F test was used for comparison purposes.

Significant differences between groups ($p < 0.05$) were determined by a one-way ANOVA followed by a Tukey-Kramer post hoc test correcting for multiple comparisons or a t test. Differences between treatment conditions were determined within each age group, comparing peak time in age-appropriate untreated slices with drug treatments. All results are reported as mean \pm SEM. For the electrophysiology data, treatment effects were analyzed within age groups by one-way ANOVA followed by Tukey-Kramer multiple comparisons or a t test. Differences between treatment conditions were determined within each age group, comparing peak time in age-appropriate untreated slices with drug treatments. Real-time PCR data were analyzed by comparison of Δ CT values by two-way ANOVA (ZT time \times age as factors) with Tukey-Kramer multiple comparisons post hoc test for each subunit.

3. Results

3.1. Light-driven behavioral clock resetting is attenuated in aged mice

The effects of both dim (30 lux) and bright (300 lux) fluorescent white light were studied on their ability to reset behavioral circadian rhythms in young and old mice. Young mice displayed a characteristic intensity-dependent response with greater phase shifts observed on exposure to a 300 lux stimulus (-150 ± 5 minutes [mean \pm SEM]; $n = 14$, two-way ANOVA, $F_{(3,39)} = 105.3$, $p < 0.0001$, Fig. 1A) relative to 30 lux (-80 ± 4 minutes, $n = 14$). A similar trend was observed in older mice where an order of magnitude increase in light intensity resulted in shifts significantly greater than those to a dim light, with resulting shifts of -74 ± 6 ($n = 14$, $p < 0.0001$) and -35 ± 3 ($n = 14$) minutes, respectively. However, under both photic conditions, younger mice demonstrated significantly greater phase shifts ($p < 0.0001$) relative to the aged mice with approximately 50% increases in response to dim and bright light pulses. Two-way ANOVA indicated that age accounted for 84.31% of the variance in our data set relative to light intensity, which accounted for 5.28% [$F_{(13,39)} = 1.52$, $p > 0.05$].

3.2. Reduced pupillary light reflex sensitivity in old mice

The observed diminishing effects of light at a behavioral level is interesting; however, it is unclear if this effect was due to critical changes across the photic transduction pathway or at the level of the SCN. To dissect out possible contributing factors, we began by looking at retinal sensitivity, that is, the point at which photic signals are initially interpreted. The pupillary light reflex serves as an excellent, high-resolution indicator of direct photoreceptor decoding of light (Lucas et al., 2012). Dark-adapted mice were exposed to

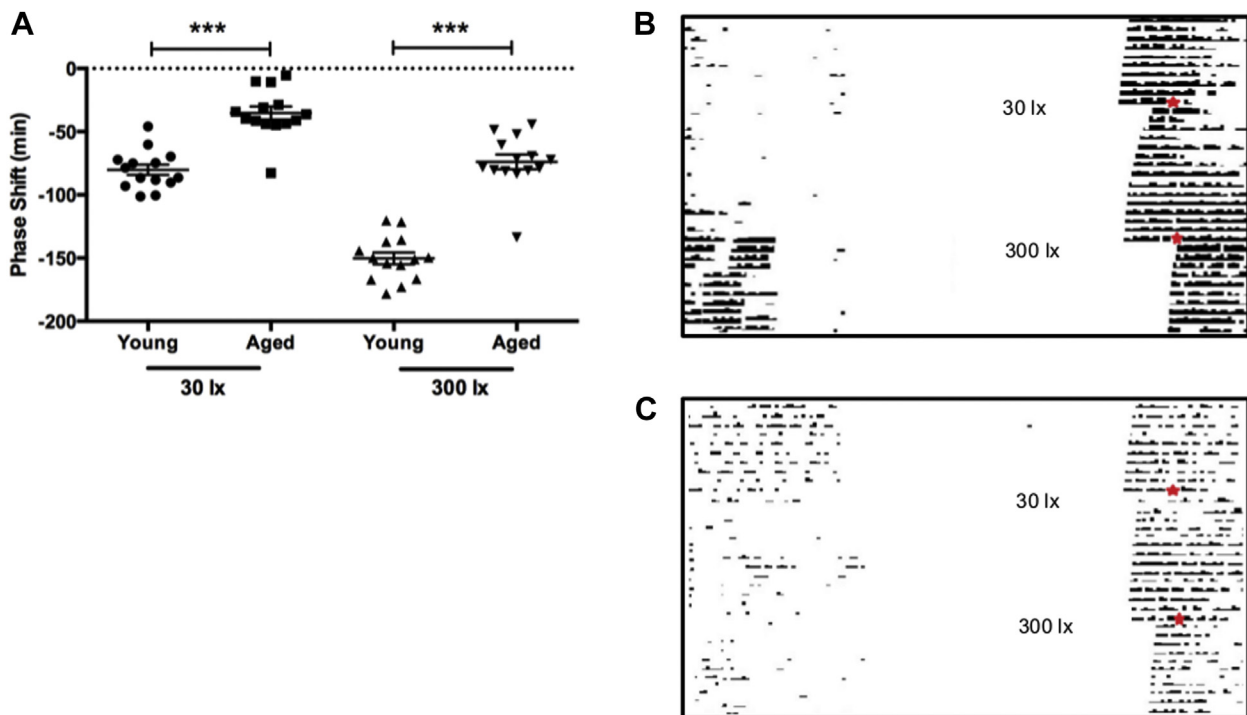


Fig. 1. Circadian behavioral resetting to light in aged mice. Older mice ($n = 14$) show attenuated behavioral responses to both saturating (300 lx) and subsaturating (30 lx) light stimuli compared to younger animals ($^{***}p < 0.001$, $n = 14$) (A). Young (\bullet , \blacktriangle) and aged mice (\blacksquare , \blacktriangledown) exhibit an intensity-dependent response to light, with greater phase shifts observed in those mice receiving the higher intensity stimulus. Representative actograms displaying both responses to 30 and 300 lx in a young (B) and aged (C) mouse model; day and time of stimulus is indicated by \star .

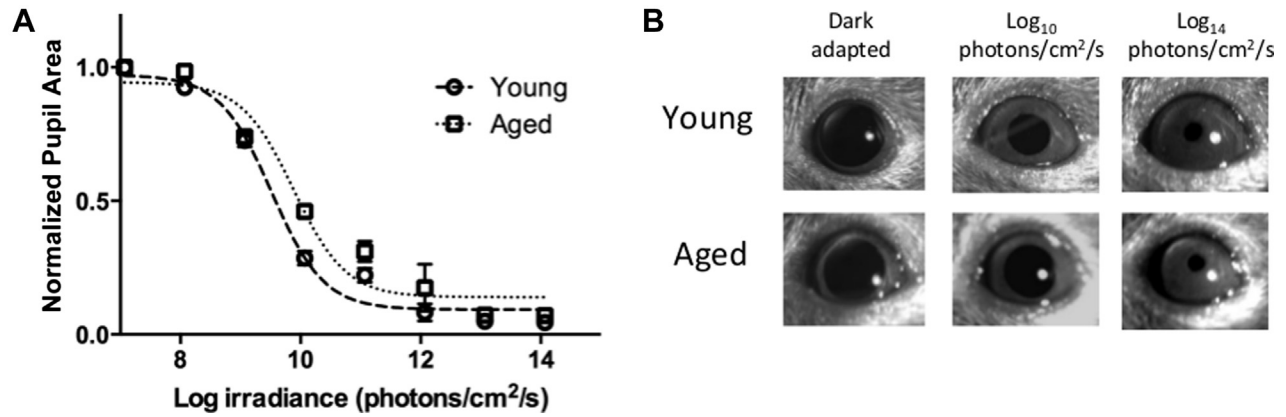


Fig. 2. Irradiance response curves for “steady state pupil size” in young and old mice. (A) Consensual pupil constrictions to white light demonstrated a shift in sensitivity between young ($n = 8$) and old mice ($n = 8$). Following curve fit analysis (A), the LogEC_{50} was greater in the aged group ($p < 0.05$); thus, aged animals show an overall decrease in sensitivity to light relative to their younger counterparts. Representative pupil images (B) show stable dark-adapted pupil sizes in both young and aged animals, with decreasing pupil areas when exposed to intermediate (Log_{10} photons/ cm^2/s) and bright (Log_{14} photons/ cm^2/s) irradiances.

a range of light intensities from very bright, 14 log photons/ cm^2/s to diminishing light in neutral density stops up to a total of 7 log units. Once plotted, we analyzed our data by applying a least squares curve fit extrapolation ($R^2 = 0.95$ for young animals and $R^2 = 0.87$ for old) and comparison using the extra-sum-of-squares F test (Fig. 2A). We found that there was a significant shift between the two groups, with younger mice having a greater sensitivity, $\text{LogEC}_{50} = 9.519$ in comparison to older animals, $\text{LogEC}_{50} = 9.883$ [$F_{(1,116)} = 5.494$, $p < 0.05$, $n = 8$].

3.3. Glutamatergic signaling is impaired in the SCN of old mice

To assess the contribution of the glutamatergic-signaling cascade in the attenuation of light-driven clock resetting, we targeted the NMDA receptor as a likely candidate. Central administration of NMDA (10 mM) at the level of the SCN in vivo resulted in significantly greater behavioral phase shifts in young mice compared to older counterparts with delays of 54 ± 9 ($n = 9$, $t = 3.38$, $p < 0.01$) and 12 ± 9 ($n = 11$, Fig. 3A) minutes, respectively.

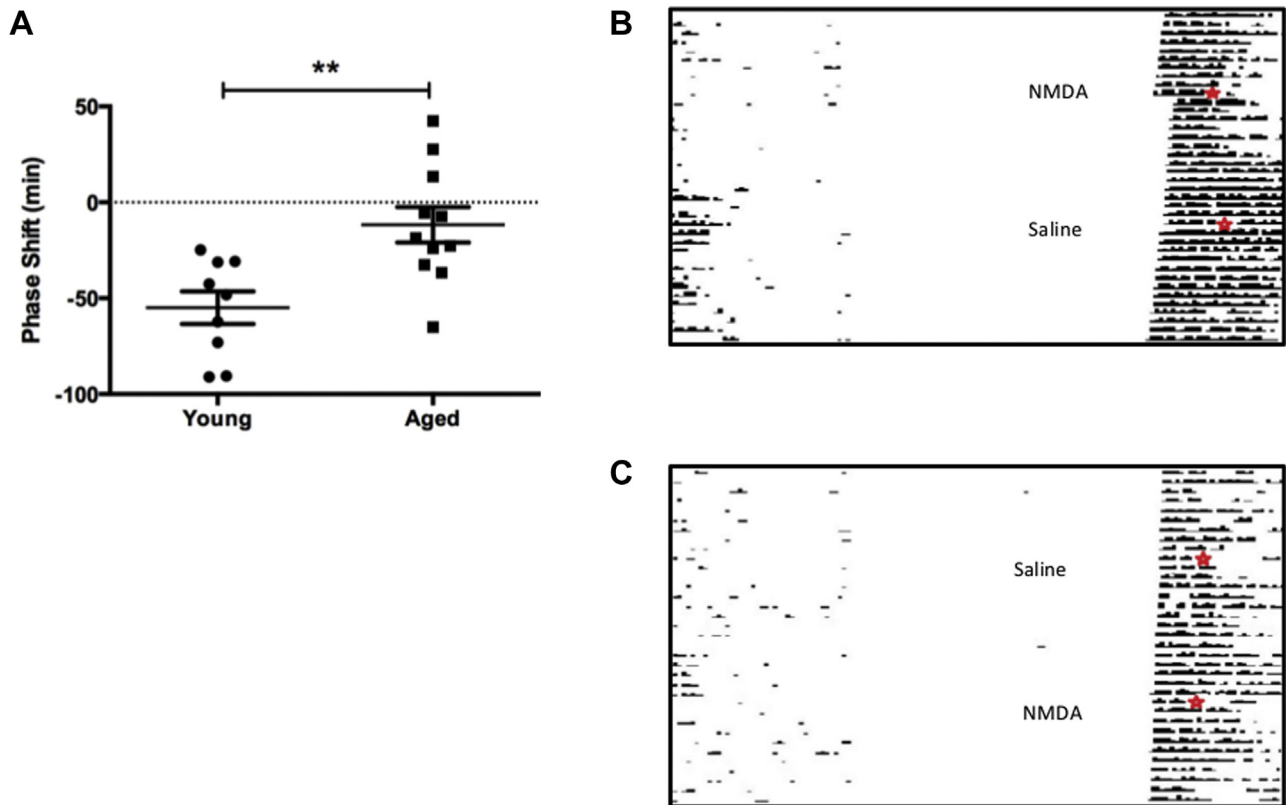


Fig. 3. Circadian behavioral resetting to NMDA in aged mice. Central injections of NMDA reset behavioral circadian rhythms in young animals (A (●) and B, $p < 0.01$, $n = 9$) however had very little impact in older mice (A (■) and B, $n = 11$). NMDA microinjections, in vivo, result in behavioral clock resetting in a similar manner to light. This response was significantly reduced in older animals ($p < 0.01$, A). Representative actograms for a young (B) and aged (C) mouse undergoing either NMDA or saline treatments; day and time of injections is indicated by ★. Abbreviation: NMDA, N-Methyl-D-aspartate.

The behavioral effects of NMDA were further isolated to the SCN through coronal slice recordings of spontaneous electrical firing rhythms in young and aged mice. Young mice displayed shifts in SCN firing peak rhythms of -232 ± 7 minutes ($n = 6$, Fig. 4A) from controls following application of NMDA. However, old mice only displayed shifts of -100 ± 14 minutes ($n = 7$), significantly less than younger mice ($p < 0.0001$, $t = 8.084$). In addition, there was also an observed decrease in the peak amplitude of firing in the aged samples ($n = 7$; 4.07 ± 0.21 Hz [mean \pm SEM]) as compared with the young ($n = 6$; 6.02 ± 0.15 Hz, $p < 0.01$), as previously reported (Biello, 2009; Nakamura et al., 2011).

3.4. NR2B expression is dramatically diminished in old mice

Having found significant alterations in NMDA signaling, both behaviorally and centrally at the level of the SCN, we went on to investigate if changes in specific NMDA subunit expression were contributing to a decline in this response. Age-dependent variations in day (ZT 6) and night (ZT 18) expression of the NMDA receptor subunits NR1, NR2A, and NR2B in the SCN were assessed using real-time PCR.

Analysis of the NR1 subunit by two-way ANOVA showed a significant effect of time [$F_{(1,16)} = 15.33$, $p = 0.0012$] and age [$F_{(1,16)} = 12.08$, $p = 0.0031$] with no significant interaction [$F_{(1,16)} < 0.001$, $p = 0.987$, $n = 3-7$]. There was a significant interaction between time and age [$F_{(1,15)} = 10.89$, $p = 0.0049$] in the expression of NR2A within the SCN, with no individual effects of either factors [time: $F_{(1,15)} = 1.634$, $p = 0.221$, age: $F_{(1,15)} = 0.0023$, $p = 0.962$, $n = 3-7$].

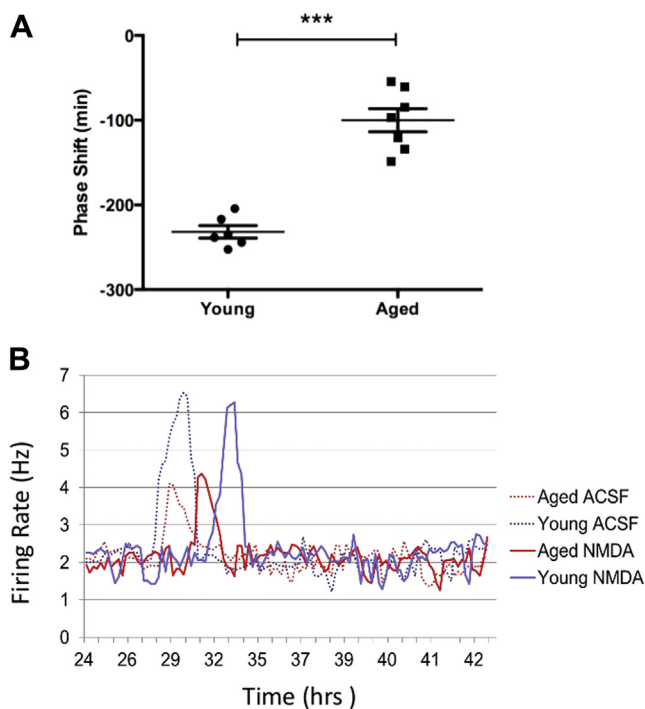


Fig. 4. Cellular firing rhythms in SCN brain slices from young and aged mice. (A) Electrophysiological recordings from isolated aged SCN brain slices displayed attenuated shifts in the peak firing rhythms following exposure to NMDA in comparison with preparations from younger animals ($***p < 0.001$, $n = 6$ young mice; $n = 7$ aged mice). (B) There was also an observed decrease in the peak amplitude of firing in the aged samples ($n = 7$; 4.07 ± 0.21 Hz [mean \pm SEM]) relative to recordings taken from young mice ($n = 6$; 6.02 ± 0.15 Hz, $p < 0.01$). Here, we show the frequency of SCN cell firing rates represented by a 1-hour running mean with a 15-minute lag over time for 4 individual slices recorded from young and aged mice. Abbreviations: NMDA, N-Methyl-D-aspartate; SCN, suprachiasmatic nucleus; SEM, standard error of the mean.

Age-dependent multiple comparisons showed significantly higher levels of NR1 ($p = 0.047$) and NR2A ($p = 0.01$) in the aged SCN during the day (Fig. 5A). However, the NR2B subunit showed a significantly age-dependent decrease in expression [$F_{(1,16)} = 54.40$, $p < 0.001$] that was not dependent on time of day [$F_{(1,16)} = 0.818$, $p = 0.379$] or an interaction of factors [$F_{(1,16)} = 0.896$, $p = 0.358$, $n = 3-7$]. During the night, no significant change was observed in either the NR1 subunits or NR2A subunits between the young and old, but the NR2B exhibited lower expression in aged mice ($p < 0.001$, Fig. 5B).

3.5. Inhibition of the NR2B subunit attenuates behavioral phase shifts to light in young but not old mice

The reduction in expression of the NR2B subunit in the SCN of old mice strongly suggested that it could be a key contributor in the behavioral changes observed in light-induced circadian responses of aged animals. To assess this hypothesis, light pulses were presented to young and old mice pretreated with the NR2B antagonist, Ifenprodil ($6.1 \mu\text{M}$). Control groups consisting of central vehicle injections followed by a light pulse resulted in reduced phase shifts in older animals relative to younger mice, with delays of 37 ± 3 (mean \pm SEM, $n = 10$) and 78 ± 3 ($n = 14$) minutes, respectively ($p < 0.001$). Following a two-way ANOVA, it was found that there was significant interaction between age and Ifenprodil treatment [$F_{(1,44)} = 44.78$, $p < 0.0001$]. Inhibition of the NR2B subunit using the antagonist Ifenprodil reduced the resetting effects of light by approximately 60% in young animals when compared to light with

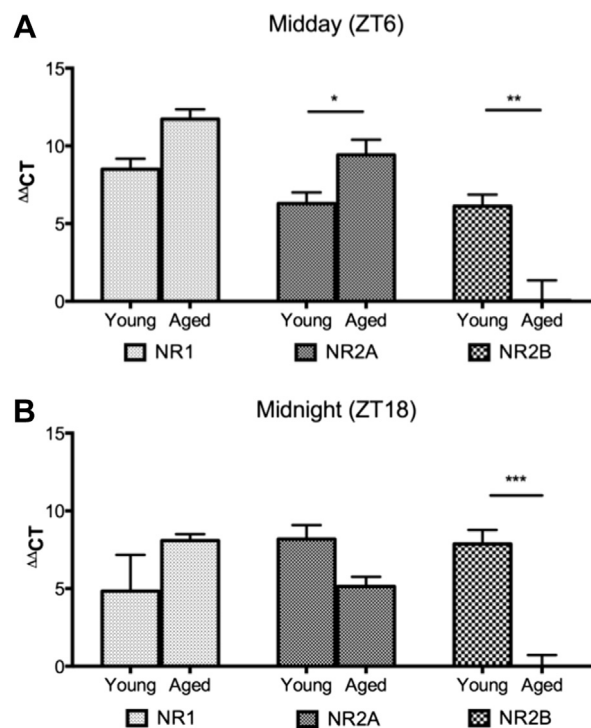


Fig. 5. Diurnal expression of NMDA receptor subunits in the SCN. Relative expression ($\Delta\Delta\text{CT}$) of NMDA subunits from SCN tissue was assessed at two time points by RT-PCR, (A) midday (ZT 6) and (B) midnight (ZT 18). Midday samples showed age-dependent changes in the expression of NR2A and NR2B ($p < 0.05$, $***p < 0.01$, $n = 3-7$). Midnight samples showed an age-dependent decline in NR2B expression in aged mice relative to the younger cohort ($***p < 0.001$). Abbreviations: NMDA, N-Methyl-D-aspartate; RT-PCR, real-time polymerase chain reaction; SCN, suprachiasmatic nucleus; ZT, Zeitgeber time.

vehicle administration in this group [$F_{(1,44)} = 13.16$, $p < 0.0001$, Fig. 6A] with resulting shifts of 30 ± 2 minutes and 78 ± 3 minutes ($n = 14$), respectively. Interestingly, injections of Ifenprodil before light stimulation in aged mice did not alter the magnitude of the response when compared with light plus vehicle treatments, with delays of 51 ± 7 minutes and 37 ± 6 minutes ($n = 10$), respectively. Although in this experiment we saw unexpected scatter of results, even with the level of variation in the vehicle-treated aged group, we were still powered for a difference of ± 21 minutes. Yet, the results from the drug-treated group gives no indication of a difference in response similar to the decreased shift we observed in the young mice, and our statistical tests (both the planned parametric and a post hoc nonparametric Kruskal-Wallis test) showed no significant difference between the groups.

4. Discussion

The data from this study provide evidence, for the first time, that shows circadian photoentrainment is impaired in aged animals through changes in SCN glutamatergic input. We have demonstrated that older mice show reduced circadian resetting to light. With only a modest change observed in pupillary light sensitivity, this effect most likely resides at the level of the SCN, where NMDA application, both in vivo and in vitro, resulted in attenuated phase shifts in aged animals. In addition, we have established that aged mice show dramatically decreased SCN expression of the NMDA NR2B subunit. Finally, we tested the functional importance of the NR2B subunit in mediating phase shifts to light in vivo. The NR2B selective antagonist, Ifenprodil, was able to inhibit clock resetting in young animals; however, no effect was observed in aged mice. Taken together, our data link the reduction in expression of the NR2B subunit to the diminishing sensitivity of the SCN to light and the resultant impact on photoentrainment.

The most common attribute associated with normal aging is that of alterations in sleeping routines (Carrier et al., 2017; Feinberg et al., 1967; Ohayon et al., 2004). These typically manifest as reduced sleep duration and increased awakening frequency during the night (Klerman et al., 2004). Such changes can be observed in humans aged from as early as 20 years and upward (Carrier et al., 1997; Landolt et al., 1996; Luca et al., 2015). Older humans show advanced sleep phase (sleeping and waking earlier), greater disruption of sleep in response to circadian misalignment, and an increased prevalence of shift work disorder (Duffy et al., 2015). Key circadian physiological markers that show misalignment include core body temperature, melatonin and cortisol secretions, urine production and higher level behavioral functions such as awareness and cognition (Campbell and Dawson, 1992; Carrier et al., 1999; Czeisler et al., 1992; Duffy et al., 2016; Sharma et al., 1989; Silva et al., 2010; Valentinuzzi et al., 1997). Alterations in circadian photoentrainment, such as those presented in this study, are likely to be fundamental to these physiological misalignments associated with age. Here, we present data showing alterations in light input signaling to the SCN, suggesting central nervous system changes likely contribute to such circadian desynchronization.

The aging eye is susceptible to a number of anatomical and functional changes. Yellowing/opaque of the lens is common in the elderly and reduces transmission of short wavelengths of light (Rukmini et al., 2017). In addition, physiological changes at the retina due to alterations in cell morphology or death are also prevalent, either due to natural aging or disease, such as glaucoma (Lin et al., 2016). Thus, the eye presents as a potential candidate for limiting light input to the SCN. We assessed age-related retinal function through the pupillary response to light in our animals, to determine if changes in sensitivity in the eye could explain the attenuated phase resetting to light. At the brightest light intensities, both young and old pupil constrictions were virtually identical,

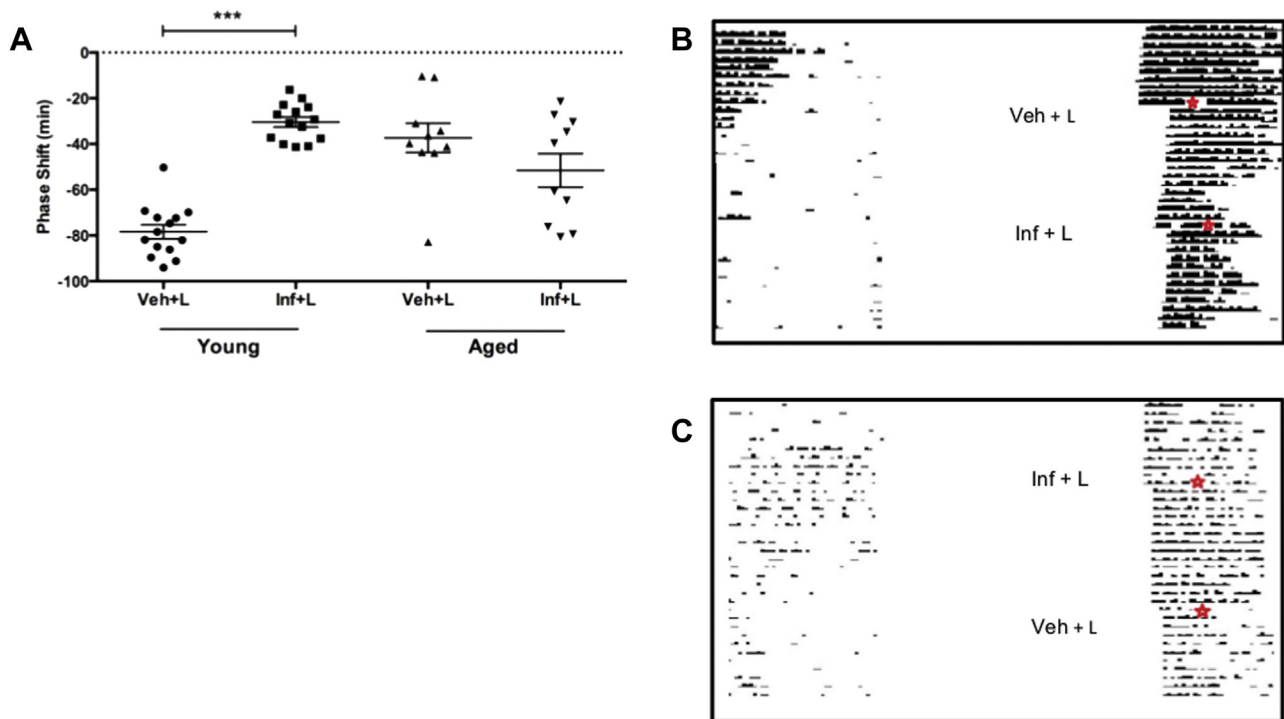


Fig. 6. Behavioral resetting mediated through the NR2B subunit. (A) Administration of the NR2B antagonist Ifenprodil, via a cannula aimed at the SCN, attenuated the resetting effects of light (150 lux) in young mice (●, ■, $p < 0.001$, $n = 14$). However, there was no level of inhibition observed in aged animals (▲, ▼, $p > 0.05$, $n = 10$). Representative locomotor records for young (B) and aged (C) mice undergoing vehicle (Veh), light (L), and/or NR2B antagonist (Inf) treatment; day and time of stimulus is indicated by ★. Abbreviation: SCN, suprachiasmatic nucleus.

indicative of a fully functioning melanopsin-induced phototransduction pathway. Given that this photoreceptor is the most important for circadian clock resetting, it is unlikely that age-related changes in the retina contribute to the behavioral deficits that we have reported (Freedman et al., 1999). The shift in pupillary sensitivity observed was mainly through responses to intermediate light (Fig. 2A), which are largely associated with cone photoreceptors, but there is little evidence supporting the involvement of cones in circadian behavioral resetting (Lall et al., 2010). Humans show loss of melanopsin-immunoreactive retinal ganglion cells after 70 years of age, with loss of the dendritic arbor apparent after age of 50 years (Esquiva et al., 2017). Furthermore, older people have a smaller pupil than younger controls, but pupillary response to light does not differ with age in people (Daneault et al., 2012). Thus, we cannot rule out a role of the aged eye as a contributor to the deteriorating photic input to the SCN; however, this is likely to have minimal effect on our results due to the higher, melanopsin-favored irradiances used in our photoentrainment protocols.

Our electrophysiological recordings from SCN slices showed a decreased SCN firing amplitude in aged mice relative to the young (Fig. 4B), supporting previously published data (Biello, 2009; Farajnia et al., 2012; Nakamura et al., 2015, 2011). Individual SCN neurons do not appear to show loss of amplitude, but cellular coupling appears to be weakened, an effect that can be counteracted by strong light-dark cycles (Farajnia et al., 2014). Our research suggests that these critically important synchronizing effects of light on SCN cells are impaired with aging. The deficits observed in resetting to photic stimuli as mice age correspond with molecular changes within the SCN (Benloucif et al., 1997; Zhang et al., 1996). These include a reduction in the photic activation of c-fos mRNA or FOS protein of the cyclic adenosine monophosphate (cAMP) response element binding protein and induction of Per1 (Kolker et al., 2003; Zhang et al., 1996). Our previous *in vitro* resetting work (Biello, 2009) suggested that these molecular changes were at least partially due to alterations at the NMDA receptor. We have further extended this to understand how changes in the NR2B subunit contribute to a portion of observed changes in responses to light with age.

The NMDA receptor presents as a multimeric protein complex consisting of an NR1 subunit and a varying number of NR2 subtypes (Cull-Candy et al., 2001; McBain and Mayer, 1994). The NR2 subunit defines the pharmacological properties of the receptor. For instance, an NR1 and NR2B combination displays slower kinetic properties with high permeability to Ca^{2+} ions (McBain and Mayer, 1994). Such attributes are likely to be favorable for relaying photic information to the SCN, allowing the greatest probability of cellular excitation through the inward flow of Ca^{2+} ions. In addition, there is also evidence of rapid switching of subunits; for example, NR2B and NR2A exchanges have been found in the visual cortex following light exposure (Quinlan et al., 1999). Our analysis of NMDA receptor subunit expression revealed variation in expression of NR1, NR2A, and NR2B across midday and midnight as well as between young and old mice. Our most striking finding was the significant decrease in NR2B expression in the old animals at both times of the day. Thus, this would suggest that aged animals have a higher proportion of NR1-NR2A receptor structures, potentially impacting glutamatergic transmission to the SCN. Furthermore, there is also some suggestion of a circadian subunit expression profile, with an overall upregulation in all subunits during the night in the young, with NR2B rhythmicity previously reported (Bendova et al., 2012; Wang et al., 2008). However, this warrants further detailed investigation and is beyond the scope of the present study.

Variations in receptor expression at the mRNA level do not always necessarily translate to physiological relevance. Thus, to this end, we tested to see if the reduced expression in NR2B was

physiologically significant. Ifenprodil is an antagonist that binds to NMDA receptors containing the NR2B subunit and shows a 200-fold preference for this configuration over other permutations (Neyton and Paoletti, 2006; Williams, 2001, 1993). Central injection of ifenprodil directly onto the SCN *in vivo* attenuated light-induced phase shifts in the young, showing a role of NR2B-containing receptors in mediating light signaling within the SCN. Significantly, there was an absence of any effect of the antagonist in aged animals, thus affirming the NR2B subunit as a likely candidate for the decline in glutamate signaling to the SCN in old mice.

Our study was undertaken in male C57BL/6J mice, which is an established model for circadian research. Circadian behavioral measures in mice are influenced by hormonal status (Krizo and Mintz, 2015). A recent meta-analysis concluded that male mice can show increased variability in behavioral measures, especially so when group-housed (Prendergast et al., 2014). While female mice show increased variability in behavioral activity across the 4-day estrus cycle, males show minimal day to day variations and increased variation within a day (Smarr et al., 2017). Retina, SCN, and the central nervous system are target regions of the SCN and all express receptors for gonadal hormones, indicating the possibility for multiple levels of interactions with sex (Bailey and Silver, 2014). There is emerging evidence that suggests sex differences in the regulation of both sleep and circadian rhythms through age, predominantly due to sex hormone expression (Carrier et al., 2017; Kuljis et al., 2013). Thus, future animal studies would benefit from including sex as a significantly important variable in assessing the impact of aging on maintenance and regulation of circadian rhythms.

We designed our studies of photoentrainment using short light pulses, allowing us measures of changes with age and following administration of pharmacological agents. Our mice were housed in constant darkness, a condition that highlights changes with age that can be masked by LD cycles (Nakamura et al., 2015). A limitation of this approach is that while mice show robust phase delays to short light pulses, phase advances are smaller, being less than an hour even in young control mice (Spoelstra et al., 2004). Studies using shifts of full light:dark cycles have shown that older mice show reduced resetting to advances of the full LD cycle (Leise et al., 2013; Valentenuzzi et al., 1997), leading us to anticipate that our current research findings extend to phase advances, but this should be explicitly tested in future studies.

5. Conclusion

In summary, we have found that the aging process impairs behavioral circadian clock resetting to light, an essential component for environmental photoentrainment. Furthermore, through electrophysiological recordings and real-time expression analysis of SCN tissue, we have narrowed down the NMDA NR2B subunit as a significant key contributor to age-induced decline in light sensitivity. Most significantly, we have shown this to be the case *in vivo*, thus providing functional evidence inferred from our molecular and cellular data. Overall, in the aging mammalian circadian system, it would appear that the alterations in glutamatergic drive to the SCN through the NMDA receptor play a fundamental role in the challenges faced by the circadian clock in generating a stable and robust photoentrained rhythm. Finally, by establishing the significant changes in NMDA receptor configuration through age and the impact on circadian synchronization, we have uncovered a novel therapeutic target for the potential treatment of circadian misalignment in aged individuals.

Disclosure statement

All authors report no actual or potential conflicts of interest.

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References

- Bailey, M., Silver, R., 2014. Sex differences in circadian timing systems: implications for disease. *Front. Neuroendocrinol.* 35, 111–139.
- Bendová, Z., Sládek, M., Svobodová, I., 2012. The expression of NR2B subunit of NMDA receptor in the suprachiasmatic nucleus of Wistar rats and its role in glutamate-induced CREB and ERK1/2 phosphorylation. *Neurochem. Int.* 61, 43–47.
- Benloucif, S., Masana, M.I., Dubocovich, M.L., 1997. Light-induced phase shifts of circadian activity rhythms and immediate early gene expression in the suprachiasmatic nucleus are attenuated in old C3H/HeN mice. *Brain Res.* 747, 34–42.
- Biello, S.M., 2009. Circadian clock resetting in the mouse changes with age. *Age (Omaha)* 31, 293–303.
- Biello, S.M., Golombek, D.A., Schak, K.M., Harrington, M.E., 1997. Circadian phase shifts to neuropeptide Y *In vitro*: cellular communication and signal transduction. *J. Neurosci.* 17, 8468–8475.
- Bonsall, D.R., Lall, G.S., 2013. Protein kinase C differentially regulates entrainment of the mammalian circadian clock. *Chronobiol. Int.* 30, 460–469.
- Campbell, S., Dawson, D., 1992. Aging young sleep: a test of the phase advance hypothesis of sleep disturbance in the elderly. *J. Sleep Res.* 1, 205–210.
- Carrier, J., Monk, T.H., Buysse, D.J., Kupfer, D.J., 1997. Sleep and morningness-eveningness in the “middle” years of life (20–59 y). *J. Sleep Res.* 6, 230–237.
- Carrier, J., Monk, T.H., Reynolds 3rd, C.F., Buysse, D.J., Kupfer, D.J., 1999. Are age differences in sleep due to phase differences in the output of the circadian timing system? *Chronobiol. Int.* 16, 79–91.
- Carrier, J., Semba, K., Deurveilher, S., Drogos, L., Cyr-Cronier, J., Lord, C., Sekerovick, Z., 2017. Sex differences in age-related changes in the sleep-wake cycle. *Front. Neuroendocrinol.* 40, 66–85.
- Colwell, C.S., Ralph, M.R., Menaker, M., 1990. Do NMDA receptors mediate the effects of light on circadian behavior? *Brain Res.* 523, 117–120.
- Cull-Candy, S., Brickley, S., Farrant, M., 2001. NMDA receptor subunits: diversity, development and disease. *Curr. Opin. Neurobiol.* 11, 327–335.
- Czeisler, C.A., Dumont, M., Duffy, J.F., Steinberg, J.D., Richardson, G.S., Brown, E.N., Sánchez, R., Ríos, C.D., Ronda, J.M., 1992. Association of sleep-wake habits in older people with changes in output of circadian pacemaker. *Lancet* 340, 933–936.
- Daneault, V., Vandewalle, G., Hébert, M., Teikari, P., Mure, L.S., Doyon, J., Gronfier, C., Cooper, H.M., Dumont, M., Carrier, J., 2012. Does pupil constriction under blue and green monochromatic light exposure change with age? *J. Biol. Rhythms* 27, 257–264.
- Ding, J.M., Chen, D., Weber, E.T., Faiman, L.E., Rea, M.A., Gillette, M.U., 1994. Resetting the biological clock: mediation of nocturnal circadian shifts by glutamate and NO. *Science* 266, 1713–1717.
- Duffy, J.F., Zitting, K.M., Chinoy, E.D., 2015. Aging and circadian rhythms. *Sleep Med. Clin.* 10, 423–434.
- Duffy, J.F., Scheuermaier, K., Loughlin, K.R., 2016. Age-related sleep disruption and reduction in the circadian rhythm of urine output: contribution to Nocturia? *Curr. Aging Sci.* 9, 34–43.
- Duncan, M.J., Herron, J.M., Hill, S.A., 2001. Aging selectively suppresses vasoactive intestinal peptide messenger RNA expression in the suprachiasmatic nucleus of the Syrian hamster. *Mol. Brain Res.* 87, 196–203.
- Ebling, F.J.P., 1996. The role of glutamate in the photic regulation of the suprachiasmatic nucleus. *Prog. Neurobiol.* 50, 109–132.
- Esquiva, G., Lax, P., Pérez-Santónja, J.J., García-Fernández, J.M., Cuenca, N., 2017. Loss of melanopsin-expressing ganglion cell subtypes and dendritic degeneration in the aging human retina. *Front. Aging Neurosci.* 9, 79.
- Farajnia, S., Michel, S., Deboer, T., vanderLeest, H.T., Houben, T., Rohling, J.H.T., Ramkisoensing, A., Yassenkov, R., Meijer, J.H., 2012. Evidence for neuronal Desynchrony in the aged suprachiasmatic nucleus clock. *J. Neurosci.* 32, 5891–5899.
- Farajnia, S., Deboer, T., Rohling, J.H.T., Meijer, J.H., Michel, S., 2014. Aging of the suprachiasmatic clock. *Neuroscientist* 20, 44–55.
- Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A., 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191.
- Faul, F., Erdfelder, E., Buchner, A., Lang, A.-G., 2009. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. *Behav. Res. Methods* 41, 1149–1160.
- Feinberg, I., Koresko, R.L., Heller, N., 1967. EEG sleep patterns as a function of normal and pathological aging in man. *J. Psychiatr. Res.* 5, 107–144.
- Flores-Soto, M.E., Chaparro-Huerta, V., Escoto-Delgado, M., Vazquez-Valls, E., González-Castañeda, R.E., Beas-Zarate, C., 2012. [Structure and function of NMDA-type glutamate receptor subunits]. *Neurología* 27, 301–310.
- Freedman, M.S., Lucas, R.J., Soni, B., von Schantz, M., Muñoz, M., David-Gray, Z., Foster, R., 1999. Regulation of mammalian circadian behavior by non-rod, non-cone, ocular photoreceptors. *Science* 284, 502–504.
- Gillette, M.U., 1986. The suprachiasmatic nuclei: circadian phase-shifts induced at the time of hypothalamic slice preparation are preserved *in vitro*. *Brain Res.* 379, 176–181.
- Gu, C., Coomans, C.P., Hu, K., Scheer, F.A.J.L., Stanley, H.E., Meijer, J.H., 2015. Lack of exercise leads to significant and reversible loss of scale invariance in both aged and young mice. *Proc. Natl. Acad. Sci.* 112, 2320–2324.
- Kawakami, F., Okamura, H., Tamada, Y., Maebayashi, Y., Fukui, K., Ibata, Y., 1997. Loss of day-night differences in VIP mRNA levels in the suprachiasmatic nucleus of aged rats. *Neurosci. Lett.* 222, 99–102.
- Klerman, E.B., Davis, J.B., Duffy, J.F., Dijk, D.-J., Kronauer, R.E., 2004. Older people awaken more frequently but fall back asleep at the same rate as younger people. *Sleep* 27, 793–798.
- Kolker, D.E., Fukuyama, H., Huang, D.S., Takahashi, J.S., Horton, T.H., Turek, F.W., 2003. Aging alters circadian and light-induced expression of clock genes in Golden Hamsters. *J. Biol. Rhythms* 18, 159–169.
- Krajnc, K., Kashon, M.L., Rosewell, K.L., Wise, P.M., 1998. Aging alters the rhythmic expression of vasoactive intestinal polypeptide mRNA but not arginine vasopressin mRNA in the suprachiasmatic nuclei of female rats. *J. Neurosci.* 18, 4767–4774.
- Krizo, J.A., Mintz, E.M., 2015. Sex differences in behavioral circadian rhythms in laboratory rodents. *Front. Endocrinol. (Lausanne)* 5, 234.
- Kuljis, D.A., Loh, D.H., Truong, D., Vosko, A.M., Ong, M.L., McClusky, R., Arnold, A.P., Colwell, C.S., 2013. Gonadal- and sex-chromosome-dependent sex differences in the circadian system. *Endocrinology* 154, 1501–1512.
- Kumar, A., 2015. NMDA receptor function during senescence: implication on cognitive performance. *Front. Neurosci.* 9, 1–15.
- Lall, G.S., Revell, V.L., Momiji, H., Al Enezi, J., Altimus, C.M., Güler, A.D., Aguilar, C., Cameron, M.A., Allender, S., Hankins, M.W., Lucas, R.J., 2010. Distinct contributions of rod, cone, and melanopsin photoreceptors to encoding irradiance. *Neuron* 66, 417–428.
- Landolt, H.P., Dijk, D.J., Achermann, P., Borbély, A.A., 1996. Effect of age on the sleep EEG: Slow-wave activity and spindle frequency activity in young and middle-aged men. *Brain Res.* 738, 205–212.
- Leise, T.L., Harrington, M.E., Molyneux, P.C., Song, I., Queenan, H., Zimmerman, E., Lall, G.S., Biello, S.M., 2013. Voluntary exercise can strengthen the circadian system in aged mice. *Age (Omaha)* 35, 2137–2152.
- Lin, J.B., Tsubota, K., Apte, R.S., 2016. A glimpse at the aging eye. *NPJ Aging Mech. Dis.* 2, 16003.
- Livak, K.J., Schmittgen, T.D., 2001. Analysis of relative gene expression data using real-time quantitative PCR and the $2^{-\Delta\Delta C(T)}$ Method. *Methods* 25, 402–408.
- Luca, G., Haba Rubio, J., Andries, D., Tobback, N., Vollenweider, P., Waeber, G., Marques Vidal, P., Preisig, M., Heinzer, R., Tafti, M., 2015. Age and gender variations of sleep in subjects without sleep disorders. *Ann. Med.* 47, 482–491.
- Lucas, R.J., 2003. Diminished pupillary light reflex at high irradiances in melanopsin-Knockout mice. *Science* 299, 245–247.
- Lucas, R.J., Lall, G.S., Allen, A.E., Brown, T.M., 2012. How rod, cone, and melanopsin photoreceptors come together to enlighten the mammalian circadian clock. *Prog. Brain Res.* 199, 1–16.
- Madeira, M.D., Sousa, N., Santer, R.M., Paula-Barbosa, M.M., Gundersen, H.J.G., 1995. Age and sex do not affect the volume, cell numbers, or cell size of the suprachiasmatic nucleus of the rat: an unbiased stereological study. *J. Comp. Neurol.* 361, 585–601.
- Magnusson, K.R., 2000. Declines in mRNA expression of different subunits may account for differential effects of aging on agonist and antagonist binding to the NMDA receptor. *J. Neurosci.* 20, 1666–1674.
- Ohayon, M.M., Carskadon, M.A., Guilleminault, C., Vitiello, M.V., 2004. Meta-analysis of quantitative sleep parameters from childhood to old age in healthy individuals: developing normative sleep values across the human lifespan. *Sleep* 27, 1255–1273.
- Maynard, M.L., Zele, A.J., Kwan, A.S., Feigl, B., 2017. Intrinsically photosensitive retinal ganglion cell function, sleep efficiency and depression in advanced age-related macular degeneration. *Investig. Ophthalmol. Vis. Sci.* 58, 990–996.
- McBain, C.J., Mayer, M.L., 1994. N-methyl-D-aspartic acid receptor structure and function. *Physiol. Rev.* 74, 723–760.
- Mintz, E.M., Marvel, C.L., Gillespie, C.F., Price, K.M., Albers, H.E., 1999. Activation of NMDA receptors in the suprachiasmatic nucleus produces light-like phase shifts of the circadian clock *in vivo*. *J. Neurosci.* 19, 5124–5130.
- Morin, L.P., Allen, C.N., 2006. The circadian visual system, 2005. *Brain Res. Rev.* 51, 1–60.
- Nakamura, T.J., Nakamura, W., Yamazaki, S., Kudo, T., Cutler, T., Colwell, C.S., Block, G.D., 2011. Age-related decline in circadian output. *J. Neurosci.* 31, 10201–10205.
- Nakamura, T.J., Nakamura, W., Tokuda, I.T., Ishikawa, T., Kudo, T., Colwell, C.S., Block, G.D., 2015. Age-related changes in the circadian system unmasked by constant conditions. *eNeuro* 2, 1–10.
- Neyton, J., Paoletti, P., 2006. Relating NMDA receptor function to receptor subunit composition: limitations of the pharmacological approach. *J. Neurosci.* 26, 1331–1333.

- Piggott, M.A., Perry, E.K., Perry, R.H., Court, J.A., 1992. [3H]MK-801 binding to the NMDA receptor complex, and its modulation in human frontal cortex during development and aging. *Brain Res.* 588, 277–286.
- Prendergast, B.J., Onishi, K.G., Zucker, I., 2014. Female mice liberated for inclusion in neuroscience and biomedical research. *Neurosci. Biobehav. Rev.* 40, 1–5.
- Quinlan, E.M., Olstein, D.H., Bear, M.F., 1999. Bidirectional, experience-dependent regulation of N-methyl-D-aspartate receptor subunit composition in the rat visual cortex during postnatal development. *Proc. Natl. Acad. Sci. U.S.A.* 96, 12876–12880.
- Reppert, S.M., Weaver, D.R., 2002. Coordination of circadian timing in mammals. *Nature* 418, 935–941.
- Rukmini, A.V., Milea, D., Aung, T., Gooley, J.J., 2017. Pupillary responses to short-wavelength light are preserved in aging. *Sci. Rep.* 7, 43832.
- Satinoff, E., Li, H., Tcheng, T.K., Liu, T., McArthur, A.J., Medanic, M., Gillette, M.U., 1993. Do the suprachiasmatic nuclei oscillate in old rats as they do in young ones? *Am. J. Physiol.* 265, R1216–R1222.
- Schneider, C.A., Rasband, W.S., Eliceiri, K.W., 2012. NIH Image to ImageJ: 25 years of image analysis. *Nat. Methods* 9, 671–675.
- Sharma, M., Palacios-Bois, J., Schwartz, G., Iskandar, H., Thakur, M., Quirion, R., Nair, N.P.V., 1989. Circadian rhythms of melatonin and cortisol in aging. *Biol. Psychiatry* 25, 305–319.
- Silva, E.J., Wang, W., Ronda, J.M., Wyatt, J.K., Duffy, J.F., 2010. Circadian and wake-dependent influences on subjective sleepiness, cognitive throughput, and reaction time performance in older and young adults. *Sleep* 33, 481–490.
- Slattery, J.A., Page, A.J., Dorian, C.L., Brierley, S.M., Blackshaw, L.A., 2006. Potentiation of mouse vagal afferent mechanosensitivity by ionotropic and metabotropic glutamate receptors. *J. Physiol.* 577, 295–306.
- Smarr, B.L., Grant, A.D., Zucker, I., Prendergast, B.J., Kriegsfeld, L.J., 2017. Sex differences in variability across timescales in BALB/c mice. *Biol. Sex Differ.* 8, 7.
- Spoelstra, K., Albrecht, U., van der Horst, G.T.J., Brauer, V., Daan, S., 2004. Phase responses to light pulses in mice lacking functional *per* or *cry* genes. *J. Biol. Rhythms* 19, 518–529.
- Valentinuzzi, V.S., Scarbrough, K., Takahashi, J.S., Turek, F.W., 1997. Effects of aging on the circadian rhythm of wheel-running activity in C57BL/6 mice. *Am. J. Physiol.* 273, R1957–R1964.
- Wang, L.M., Schroeder, A., Loh, D., Smith, D., Lin, K., Han, J.H., Michel, S., Hummer, D.L., Ehlen, J.C., Albers, H.E., Colwell, C.S., 2008. Role for the NR2B subunit of the N-methyl-D-aspartate receptor in mediating light input to the circadian system. *Eur. J. Neurosci.* 27, 1771–1779.
- Williams, K., 1993. Ifenprodil discriminates subtypes of the N-methyl-D-aspartate receptor: selectivity and mechanisms at recombinant heteromeric receptors. *Mol. Pharmacol.* 44, 851–859.
- Williams, K., 2001. Ifenprodil, a novel NMDA receptor antagonist: site and mechanism of action. *Curr. Drug Targets* 2, 285–298.
- Wise, P.M., Cohen, I.R., Weiland, N.G., London, E.D., 1988. Aging alters the circadian rhythm of glucose utilization in the suprachiasmatic nucleus (middle age/diurnal rhythm/hypothalamus/estradiol/2-deoxyglucose). *Neurobiology* 85, 5305–5309.
- Wulff, K., 2015. The role of photoreception and light intervention for sleep and neuropsychiatric disturbances in the elderly. *Int. Psychogeriatrics* 27, 1022–1029.
- Zhang, Y., Kornhauser, J.M., Zee, P.C., Mayo, K.E., Takahashi, J.S., Turek, F.W., 1996. Effects of aging on light-induced phase-shifting of circadian behavioral rhythms, Fos expression and CREB phosphorylation in the hamster suprachiasmatic nucleus. *Neuroscience* 70, 951–961.