Human seasonal and circadian studies in Antarctica (Halley, 75°S)

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Abstract

Living for extended periods in Antarctica exposes base personnel to extremes of daylength (photoperiod) and temperature. At the British Antarctic Survey base of Halley, 75°S, the sun does not rise for 110 d in the winter and does not set for 100 d in summer. Photoperiod is the major time cue governing the timing of seasonal events such as reproduction in many species. The neuroendocrine signal providing photoperiodic information to body physiology is the duration of melatonin secretion which reflects the length of the night: longer in the short days of winter and shorter in summer. Light of sufficient intensity and spectral composition serves to suppress production of melatonin and to set the circadian timing and the duration of the rhythm. In humans early observations suggested that bright (>2000 lux) white light was needed to suppress melatonin completely. Shortly thereafter winter depression (Seasonal Affective Disorder or SAD) was described, and its successful treatment by an artificial summer photoperiod of bright white light, sufficient to shorten melatonin production. At Halley dim artificial light intensity during winter was measured, until 2003, at a maximum of approximately 500 lux in winter. Thus a strong seasonal and circadian time cue was absent. It seemed likely that winter depression would be common in the extended period of winter darkness and could be treated with an artificial summer photoperiod. These observations, and predictions, inspired a long series of studies regarding human seasonal and circadian status, and the effects of light treatment, in a small overwintering, isolated community, living in the same conditions for many months at Halley. We found little evidence of SAD, or change in duration of melatonin production with season. However the timing of the melatonin rhythm itself, and/or that of its metabolite 6-sulphatoxymelatonin (aMT6s), was used as a primary marker of seasonal, circadian and treatment changes. A substantial phase delay of melatonin in winter was advanced to summer phase by a two pulse 'skeleton' bright white light treatment. Subsequently a single morning pulse of bright white light was effective with regard to circadian phase and improved daytime performance. The circadian delay evidenced by melatonin was accompanied by delayed sleep (logs and actigraphy): poor sleep is a common complaint in Polar regions. Appropriate extra artificial light, both standard white, and blue enriched, present throughout the day, effectively countered delay in sleep timing and the aMT6s rhythm. The most important factor appeared to be the maximum light experienced. Another manifestation of the winter was a decline in self-rated libido (men only on base at this time). Women on the base showed lower aspects of physical and mental health compared to men. Free-running rhythms were seen in some subjects following night shift, but were rarely found at other times, probably because this base has strongly scheduled activity and leisure time. Complete circadian adaptation during a week of night shift, also seen in a similar situation on North Sea oil rigs, led to problems readapting back to day shift in winter, compared to summer. Here again timed light treatment was used to address the problem.

Sleep, alertness and waking performance are critically dependent on optimum circadian phase. Circadian desynchrony is associated with increased risk of major disease in shift workers. These studies provide some groundwork for countering/avoiding circadian desynchrony in rather extreme conditions.

Keywords: seasonal, circadian, light, melatonin, Antarctica

1. Introduction

Numerous human seasonal changes have been described in studies largely from temperate zones. However the extreme light conditions, shared environment and closed community of an overwintering Antarctic base provide a natural laboratory for the observation and manipulation of seasonal changes (Arendt, 2012).

The most reliable seasonal time cue in temperate and high latitudes is changing daylength or photoperiod. Photoperiodic species, for example hamsters, sheep and goats, use primarily daylength to time seasonal functions such as reproduction, behaviour and coat growth. They perceive daylength changes by the duration of melatonin secretion from the pineal gland, longer in short days and vice versa. This mechanism was elucidated in the late 1970s - early 1980s (Carter and Goldman, 1983a, Carter and Goldman, 1983b, Arendt, 1986, Woodfill et al., 1991, Goldman, 2001,). Since then considerable progress has been made regarding the downstream response in animals (Dardente, 2012, Lincoln and Loudon, 2015). However the question as to whether or not the profound reproductive and other seasonal changes as a function of photoperiod in such species also apply to some extent in humans has not been adequately answered. In humans, Seasonal Affective Disorder (SAD, winter depression) is probably the most closely linked to light conditions, being first observed in short days. It was initially treated, successfully, by artificially extending the winter daylength to a summer photoperiod using a 'skeleton' treatment (two light pulses), with extra bright light, sufficient to completely suppress melatonin secretion (Lewy et al., 1980) in the morning and the evening (Rosenthal et al., 1984). It appeared therefore that a human seasonal change was countered via a photoperiodic mechanism (although different theories are currently prominent).

In general the conservation of photoperiodic responses in humans in terms of melatonin secretion is difficult to address as it involves controlled long term imposition of particular environmental conditions. Where this was possible in temperate latitudes it was clear that changes in melatonin duration with imposed artificial photoperiod could occur in humans as they do in, for example, sheep, and they were linked to changes in duration of sleep and timing of sleep propensity (Wehr et al., 1993, Arendt, 1999, Vondrasová-Jelínková et al., 1999). The question of possible links with human reproductive function, mood and behaviour remains. There is certainly some evidence from pathology that circulating melatonin may relate to major changes in reproductive hormones e.g, (Arendt et al., 1989, Luboshitsky and Lavie, 1996, Walker et al., 1996).

Seasonal changes in the circadian timing system in humans are of closely related interest: the melatonin rhythm is the best way to date of assessing circadian timing (Klerman et al., 2002) and is extensively used for evaluating circadian status. The light-dark cycle, acting via retinal mechanisms, is the primary time cue for synchronisation of the suprachiasmatic nuclei (SCN), master pacemaker of the circadian system, to the 24h day. In the absence of sufficient time cues circadian rhythms may delay or more rarely advance with respect to the 24h day, or free-run (desynchronise completely from 24h) showing endogenous periodicity. In humans this periodicity is individually variable, genetically determined, and on average slightly longer than 24h (Czeisler, 1995, Middleton et al., 1996). A long endogenous period is more associated with subjective evening preference ('owl'), and a greater tendency to circadian delay, than a short period with morning preference ('lark') (Horne and Ostberg, 1976, Duffy et al., 2001). The amount of light needed to maintain circadian synchrony

depends on different factors. In controlled long term (1 month) studies in an environment free of time cues with the exception of clock time, we found that a 12:12 light dark cycle of 200 lux:<8 lux white light was insufficient to maintain 24h synchrony and that between 200 and 1000 lux was required (Middleton et al., 2002).

Much information on the use of light treatment to maintain synchrony has accumulated, including the importance of prior photoperiodic history (Hébert et al., 2002, Owen and Arendt, 1992), and the spectral quality of the light as well as its intensity and timing. The light phase response curve (PRC) - a measure of the magnitude and direction of phase shifts following a particular light stimulus - provides a means of predicting responses to timed light exposure (Czeisler, 1995, Chang et al., 2011, Rüger et al., 2013, Lucas et al., 2014). Providing circadian status is known or predictable, light treatment can be timed to delay or advance the circadian system.

Figure. 1. About here. Light PRC

Other time cues (zeitgebers) include scheduled mealtimes, sleep, social interactions, exercise (Mistlberger and Skene, 2005). Combined with a weak light-dark zeitgeber they can help maintain synchrony. However the predominance of alternating light and darkness is most obvious in totally blind individuals, the majority of whom show the phenomenon of free-running. Here the circadian system displays its endogenous period in a normal light dark environment in the presence of all other possible time cues, (for early references see (Lockley et al., 2007). When such individuals attempt to conform to a 24h day, awake during the daytime, sleeping at night, the deviation of the natural period from 24h means that, intermittently, they will be out of phase with the internal clock attempting to sleep at a time of maximum alertness and work at a time of maximum sleepiness (Arendt et al., 1988, Sack et al., 1992, Lockley et al., 1999b, Lockley et al., 2008). This has been referred to as a kind of recurrent jet lag, and is a lifetime problem. The most obvious symptoms in affected individuals are poor sleep and excessive daytime sleepiness/naps when out of phase. This phenomenon has been characterised as free-running sleep disorder (Morgenthaler et al., 2007). It was clearly described during the period when the sun is below the horizon (sundown) in four sighted over-winterers at Cape Evans base in Antarctica by Kennaway and van Dorp in 1991.

Circadian desynchrony, notably of shift workers has been associated with, poor sleep, lowered alertness and performance, and increased risk of major disease. The ability to maintain optimum circadian timing is of general importance to human health.

In view of the various light related phenomena described above it is clearly of interest to investigate human responses in different environmental and experimental light conditions. In 1984 the opportunity arose for the first author to design and supervise research in Antarctica on British Antarctic Survey bases with extreme environmental light changes during the year. The base doctor carried out the on-site sampling and recording, and data were analysed at the University of Surrey (with the help of Stockgrand Ltd, University of Surrey). Where possible the results formed the basis of an MSc in Remote Health Care and if suitable they were published. This short review summarises and discusses the relevant data.

2. Study conditions

Above the Polar circle latitudes of $66^{\circ} 33'$, North or South, the sun is above the horizon for 24 h for at least 1 d/yr (midsummers day) and below the horizon for 24 h for at least 1 d/yr (midwinters day). With increasing latitude, there will be more days with either no sunlight or continuous sunlight. At Halley, 75°S , the sun does not rise for 110 d in the winter and does not set for 100 d in summer. Figure 2 a and b shows actual personal light exposure and activity recorded by ActiwatchL (AWL, Cambridge Neurotechnology Ltd, UK) at Halley. During the winter with only artificial light, the maximum light exposure possible until very recently was $\approx 500\text{--}700$ lux (Broadway et al., 1987, Francis et al., 2008), whereas on a bright sunny day in summer in Polar regions, the outdoor light intensity can exceed 40,000 lux (and in temperate/equatorial regions can exceed 100,000 lux). Measured personal exposure is somewhat less on average. Thus a strong light-dark zeitgeber for circadian entrainment is absent during the winter period when the sun is below the horizon. Some adaptation to these conditions in terms of light sensitivity is seen, whereby an increased suppression of melatonin by light was found in winter compared to summer (Owen and Arendt, 1992) and the importance of photoperiodic history to melatonin suppression by light at night in temperate zones has since been emphasised by others (Chang et al., 2011, Hébert et al., 2002).

Figure.2 a and b. About here. Halley light (a) and activity (b)

It is obviously possible to generate a light-dark cycle in summer in these conditions keeping a normal routine for bedtime/sleep and having dark sleeping quarters. Nonetheless, personnel working during the night shift can experience bright light at night. The exposure to UV light is so strong that UK base personnel are required to wear sunglasses whenever outdoors in summer. To date, there is little information on what light intensity is actually experienced in Polar regions wearing sunglasses outdoors. In winter, however, the light dark cycle is dependent on artificial light.

3. The plasma melatonin rhythm in winter and summer and the effects of an artificial spring photoperiod in winter

The most obvious questions to address were whether the melatonin rhythm would change with season and whether the effect of photoperiod modification could replicate any change. No duration change was evident with season at Halley (although in different conditions on Rothera Base (67°S) a longer duration in winter has been reported (Makkison and Arendt, 1991), however there was a marked delay of the plasma melatonin rhythm in winter compared to summer (Broadway et al., 1987). The winter photoperiod was modified to give a skeleton spring photoperiod with an hour of full spectrum light administered in the morning and evening every day for 6 weeks, a control group receiving no light treatment. Subjects received ~ 2000 lux since this was reported to suppress melatonin secretion completely at night. At the time (1985) the importance of light to the circadian system had yet to be recognised thus the subjects had no preconceived idea of any possible effect. The result of the pulses of light delimiting a spring photoperiod was to phase advance the delayed winter melatonin profile (Arendt and Broadway, 1986, Arendt and Broadway, 1987, Broadway et al., 1987), Figure 4. Simultaneously and subsequently many carefully controlled experiments by others have demonstrated the phase shifting and synchronising effects of bright white light and described light PRCs in humans. Thus light can be timed specifically to manipulate the circadian system in humans. In various laboratories the investigation of the human light action spectrum for non-image forming effects of light, the identification of light sensitive

retinal ganglion cells, and the discovery of the novel photopigment melanopsin underlying circadian responses, followed on from this early work (Berson et al., 2002, Brainard et al., 2001, Czeisler, 1995, Lucas et al., 2014, Paul et al., 2009, Rüger et al., 2013, Thapan et al., 2001).

Recently (2012) a short term single light pulse treatment in midwinter at Halley (two weeks treatment, two weeks control, no treatment) with a hour of bright white light only in the morning (4775 ± 1050 lux, 8.30-9.30h) was able to advance sleep timing (actigraphy and diaries) and circadian phase (assessed using the 6-sulphatoxymelatonin (aMT6s) rhythm), consistent with the light PRC. Importantly there was a substantial improvement in performance measures (Corbett et al., 2012).

Figure 3. About here. Melatonin phase delay in winter advanced by skeleton light

A number of other measures were taken during the first Halley skeleton light experiment which will not be considered here. Suffice it to say that no evidence was found for seasonal affective disorder (SAD). Others have reported low mood (Subsyndronal SAD, SSAD) in winter-spring on some Antarctic bases including Halley (Harris et al., 2010), but in general SAD appears to be rare in the base personnel (usually healthy young men and more recently women).

4. Sleep phase delay and free-run in winter

The winter phase delay in melatonin has been reinforced in a number of studies by ourselves and others e.g. Arendt, 2012, Chen et al., 2016, Yoneyama et al., 1999. In 1989 the Halley doctor recorded a large number of variables using visual analogue scales and sleep timing using sleep diaries for 10 months of the year using most of the base personnel. An example is shown in Fig,4 where this particular subject shows a conventional wake up time (alarm clock) during the working week, but with delayed sleep onset in winter during sundown and a substantial delay of sleep timing each weekend (see Roenneberg et al., 2013 for a recent discussion of this phenomenon, sometimes called social jetlag (Wittmann et al., 2006)).

Figure.4, About here. Sleep phase delay in winter

Generally speaking a phase delay precedes overt free-running. It should be noted that a striking demonstration of the Antarctic winter effects is seen in a report from Cape Evans base (Kennaway and Van Dorp, 1991) where all four base personnel showed desynchrony in sleep (and several other variables) from 24h clock time during the winter when the sun is below the horizon, and then resynchronised once sunlight was restored. On Cape Evans base there appeared to be no particular scheduled activities except for keeping a radio watch, whereas on Halley a routine is imposed with fixed work and rest times, mealtimes, and is overseen by a base commander. It would be fair to speculate that the imposed schedule compensated in part for the dim light zeitgeber in winter. Free run exists but is quite rare at Halley except following a week of night shift (see later).

5. Libido

One of the most interesting observations during this particular year (1989) was entirely the initiative of the base doctor. He decided to record 'Libido' using a 10 cm visual analogue

scale (VAS) - 'very horny' against 'not at all horny'. Only men were staffing the base at this time. There was a clear depression of libido in winter months which begins to recover in spring (Fig 5). There may of course be many reasons for this- dim light, isolation, slightly lower activity (Fig 2), no women. However the same pattern was shown by 1st year winterers and 2nd year winterers (some people stay for 2+years) which suggests a seasonal rhythm in libido.

Figure. 5 About here. Libido O'Conor

6. Objective sleep and light recording by actigraphy

Sleep was studied by polysomnography at Halley in 1975 (Paterson, 1975). A seasonal variation in slow wave sleep was reported in a short letter to the Lancet, with reduction seen in both constant dark and constant light. Polysomnography is thought to be the 'gold standard' for objective sleep measurement, however there are few such studies on Antarctic bases no doubt for practical reasons. Actigraphy provides an acceptable methodology particularly for long term evaluation of sleep rhythms and diagnosis of circadian rhythm sleep disorders e.g. (Crowley et al., 2014, Lockley et al., 1999a, Lockley et al., 1999b).

Once actigraphy became available it was possible to record personal sleep and light exposure objectively for extended periods of time in 'field' conditions, together with circadian phase using the urinary 6-sulphatoxymelatonin rhythm. The first actigraphic sleep data from Halley (2002 - 2003) confirmed the winter decrements in sleep quality and the winter delay in sleep timing seen in subjective sleep diaries (Francis et al., 2008). It was already evident from the skeleton light treatment described above that suitable light exposure could restore summer circadian phase. In 2003 this countermeasure was revisited using an approximately 10h full photoperiod and with a comparison of blue enriched and white light, as at this time the importance of short wavelength light to the circadian system had become evident. Philips Lighting, Eindhoven, provided light boxes for each individual overwintering on the base and sufficient light boxes to illuminate communal areas and work areas (standard white, 5300K, or prototype blue-enriched, 10,000K), which were turned on in bedrooms and in communal/work areas from ~08.00h to ~18.00h. After a no-treatment control period, 28.2-20.3.2003, sequential 4-5 week periods of first white, then blue light, were imposed with a further control period from 19.9-9.10.2003.

Daily light exposure in winter (lux, $X \pm SD$) was doubled in 2003 (maximum 1039 ± 281 , average 64 ± 21), compared to 2002 (no extra light, 572 ± 276 and 30 ± 11), $p < 0.05$, and $p < 0.01$, with no differences in light levels between white and blue light. There were no major differences in circadian phase, assessed using urinary aMT6s, or sleep between light conditions in 2003: a delay in sleep timing was found in midwinter compared to control (2003, bedtime, $p < 0.05$, sleep start, $p < 0.05$, sleep end, $p < 0.01$), and sleep fragmentation increased ($p < 0.05$). Sleep efficiency was slightly higher during all blue light periods compared to all white periods ($p < 0.05$) (Francis et al., 2008).

7. A full photoperiod of sufficient intensity extra white or blue enriched light counters sleep and circadian phase delay in winter

The ongoing planning of a new Base, with a requirement for lighting specifications, and the availability of higher intensity 17000K blue enriched white light equipment (ActiViva, Active, Philips Bright Light devices) prompted a further study of sleep and circadian phase at Halley

in 2006 using the same protocol as for 2003 but with higher light intensity (Mottram et al., 2011). Maximum light exposure was doubled during sundown (11/5-11/8/2006) compared to 2003. The maximum (but not average) exposure to blue light, was slightly higher (maximum 2168 ± 405 lux, average 68.7 ± 24 lux) than the equivalent (with regard to the winter solstice) white period, (maximum 1699 ± 347 lux, average 58.4 ± 18 lux), ($p < 0.01$). The previously observed delays in midwinter wake-up time (2002, 2003) were abolished by both blue and white light (Fig 6). The delay in sleep start time was reduced compared to previous data with a clear advantage of blue light. Wake-up and sleep start time were earlier with increasing maximum light values: Wake-up versus maximum lux, $r^2 = 0.56$, $p = 0.031$, sleep start versus maximum lux, $r^2 = 0.64$, $p = 0.017$. Circadian phase assessed by the rhythm of aMT6s was earlier on average in all blue-enriched periods compared to standard white light ($p < 0.05$). On a different base a comparable use of blue enriched light had similar results (Najjar et al., 2014).

Figure 6. About here. Extra light, blue or white, prevents sleep delay in winter

Light condition had no influence on general health (Rand 36 questionnaire) but we noted that women (5 of 15 base personnel) had lower aspects of physical ($p = 0.029$) and mental health ($p = 0.001$) (Mottram et al., 2011).

The use of ActiViva light had some beneficial effects on sleep timing, length and latency compared to standard white light. However the maximum amount of light exposure per 24h, irrespective of spectral composition, is probably the most important consideration. A daily treatment with an hour (possibly less, to be determined) of very bright white morning light is inconvenient for subjects as they must be close to the light source for the treatment, but this may be the best solution for winter sleep and circadian abnormalities (Corbett et al., 2012). The best sleep timing, duration, efficiency and quality were found in control natural light conditions where maximum natural light exposure was available.

8. Shift work

In view of the dim light and delayed phase in winter, and the 24h daylight in summer an investigation into night shift work at Halley was undertaken. Each member of the base in rotation takes a turn at night shift (fire watch) for a week, from approximately 2000 - 0800h. It is possible to follow daily circadian status in shift workers using the aMT6s rhythm in urine. The sample collections are non-invasive and personnel can collect samples for days-weeks at a time. Initial observations showed that, very unusually, most night shift workers at Halley fully adapt their circadian system to night shift within a week by delaying circadian phase, but with seasonal variations. The melatonin rhythm shifts from its normal night time peak to occur during daytime sleep (Midwinter and Arendt, 1991, Ross et al., 1995, Lund et al., 2001, Ng et al., 2003). The rate at which adaptive shift occurs was closely correlated to chronotype, assessed with the Horne-Ostberg questionnaire (Horne and Ostberg, 1976): the later the chronotype the faster the shift (Ng et al., 2003). The amount of shift required to adapt is season dependent. The winter circadian delay at Halley means that the required adaptive shift is smaller than in summer (Midwinter and Arendt, 1991).

Figure 7. About here. Adapting to night shift, Ng et al., 2003

Night shift workers in temperate zones rarely show more than small circadian phase shifts (Folkard et al., 1993), an exception being workers on North Sea oil rigs (Barnes et al.,

1998a, Barnes et al., 1998b, Gibbs et al., 2002, Gibbs et al., 2007), some of which border the Arctic circle. The probable explanation in both situations (oil rigs and Antarctica) is isolation, no social demands, no, or little bright light exposure in winter during daytime sleep/leisure which could counter an adaptive circadian shift, and in summer light present during the night to reinforce circadian delay to adapt. In fact Halley personnel sleep better during night shift compared to dayshift, unlike 'normal' shift workers (Ross et al., 1995). This may relate to a more optimal phase for sleep as the circadian system delays to night mode. However the problems arise in both situations when trying to adapt back to dayshift. The adaptive phase delay (more rarely advance) may become free-run (Gibbs et al., 2002, Gibbs et al., 2007). Timed light treatment (approximately according to the light PRC) has beneficial effects on sleep for returning oil rig workers (Thorne et al., 2010). Adaptation back to day work is much slower in winter than in summer at Halley and consequent free-running can continue for weeks in winter (Fig.8). Timed light treatment, using a skeleton photoperiod can hasten re-adaptation to dayshift in winter (Midwinter and Arendt, 1991).

Figure 8. About here. Post night shift free-run, Mottram et al., 2011

8. Conclusions

These studies provide some groundwork for countering/avoiding circadian desynchrony in rather extreme conditions. Since sleep, alertness and waking performance are critically dependent on optimum circadian phase, it is not surprising that successful maintenance or re-establishment of appropriate circadian phase is associated with benefits for these behavioural variables. It is possible that a combination of timed low dose melatonin treatment in the evening combined with extra morning light would provide a further benefit for phase maintenance in winter (Arendt, 2005). The circadian desynchrony of shift workers is clearly associated with some increased risk of major disease. Everything is rhythmic unless proved otherwise, inter alia the metabolome, the cardiovascular system and the reproductive system. Further investigation is needed in Polar regions especially if more women are to be deployed to Antarctic bases.

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Declaration of interest

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Figure Legends

Figure 1. An example of a light phase response curve (PRC). Relationship of phase shift (mean+SEM) of the melatonin rhythm to the timing of the start of one hour of light treatment (hours after dim light melatonin onset or DLMO, a circadian phase marker). The light source (500 nm) was 350 lux (irradiance 98 mW/cm²+2%, manufacturer's measured specification: Sunnexbiotech.com). The photon density was 2.2!10¹⁴ photons/cm²/sec. With DLMO at 21:00 h, 6 h after DLMO corresponds to 03:00 h clock time, etc. Reproduced from Paul et al., 2009, doi:10.1080/07420520903044331. PMID:19637048

Figure 2, a and b. Personal light exposure (a) and activity (b) measured at 2-min intervals by ActiwatchL at Halley base, 75°S. Average number of subjects per time point = 7 ± 1 (SD). Data collected by Dr. Thomas Rieley, base doctor. Activity: Rieley, & Arendt, unpublished. Light: redrawn from Arendt, 2012. High light exposure in January 2000 is due to cargo discharge and loading, and low values for December 2001, are due to no relief ship and thus less outdoor work.

Figure 3. Delayed clock timing (circadian phase evidenced by the plasma melatonin rhythm) in winter, corrected by 'skeleton' 2500 lux broad spectrum white light, 1h am & pm. From Broadway et al., *Neurosci Lett* 1987, by permission.

Figure 4. Sleep (black bars) at 75°S of a representative subject showing synchronization of sleep (diaries): artificial wake-up for most week days with scheduled work and rest, but substantial phase delay on weekends in winter—May to September. From unpublished report by Dr Rory O'Connor, 1991, 'Medical research. Halley 1989' (archives ref AD6/2Z/1989/M2), reproduced courtesy of British Antarctic Survey. Redrawn from Arendt, 2012. Note three periods of night shift during the year.

Figure 5. Monthly means of daily self rated libido at Halley (1989) as a 10 cm visual analogue scale: "very horny" to "not at all horny". Of the 20 men overwintering, in 1989, 15 volunteers (7 scientists, 8 support staff) took part in all or part of the study. All were healthy men aged 26.6 ± 3.48 years (mean ± SD), 21-34 (range). Eight were wintering for the second year and seven for the first year. The number of observations for each month is given in brackets. There were no differences between the first and second year winterers. From unpublished report by Dr Rory O'Connor, 1991, 'Medical research. Halley 1989' (archives ref AD6/2Z/1989/M2), reproduced courtesy of British Antarctic Survey, redrawn.

Figure 6 a and b. a) Delay in sleep timing in winter (and circadian phase, not shown) is countered by increasing ambient light intensity for the entire 'day'. Note that wake up time during sundown is not significantly later than during the control period with natural light, in contrast to previous delays seen with insufficient artificial light. Both blue enriched (ActiViva Active) and standard white light were effective, blue being slightly more effective than white. b) The timing of sleep was closely correlated to the amounts of personal light exposure. Relationship of average wake up time and average sleep start time for each light condition. See text for details. 6a is redrawn from Mottram et al., 2010. 6b: unpublished diagram from data in Mottram et al., 2010.

Figure 7. Patterns of adaptation to night shift work. Subjective (logs) sleep times (grey bars), naps (black bars) and aMT6s acrophases (stars) in four subjects working 6 days then 6 nights at 75°S. Unpublished diagram from data in Ng, Morgan and Arendt, 2003.

Figure 8. Activity and light exposure (ActiwatchL) recorded at 30-s intervals at 75°S from May 19, 2006, to illustrate winter free-running following a period of night-shift work. Black is activity and gray is light exposure. Reproduced from Arendt, 2012, from data in Mottram et al., 2010. PMID: 20723022, doi: 10.1111/j.1365-2869.2010.00875.x.

Figure 1

Figure 2a

Figure 2b

Personal light exposure Halley 2000-2001 (log units)

Figure 3 **Delayed melatonin rhythm in winter, advanced by light pulses**

Figure 4

Sleep diary of one subject

Figure 5

Figure 6a

Figure 6b

Figure 7

Figure 8

Free-running following night shift in winter