Correspondence

A marker for the end of adolescence

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Between childhood and adulthood, we go through puberty and adolescence. While the end of puberty is defined as the point of cessation of bone growth (epiphyseal closure; girls: 16 y; boys: 17.5 y), the end of adolescence (~19 y) is defined less clearly, by a mixture of physical, psychological, social, and mental measures [1]. One conspicuous property of adolescence is the apparently unsaturable capacity to stay up late and to sleep in. Investigating 'chronotypes' we observed an abrupt change in the timing of sleep at around the age of 20 and propose this change as the first biological marker of the end of adolescence.

Chronotype refers to when an individual's endogenous circadian clock synchronises (entrains) to the 24 h day. When shielded from environmental time cues, i.e. cycles of light and darkness, circadian clocks 'run free', with a period of about one day (hence 'circa-dian'). In nature, they are entrained to the earth's 24 h light–dark cycle [2], with individual clocks entraining differently — some very late ('owls'), others very early ('larks'), and the majority in between. The chronotype is predominantly defined via behavior, e.g. activity onset in animals which strongly correlates with sleep offset.

To assess the distribution of chronotypes in the population, we use a simple questionnaire (Munich ChronoType Questionnaire, MCTQ [3]) that asks people about their sleep habits on work and free days; due to the open design of our study, the age distribution is not precisely representative (Figure 1A). The reference point to assign chronotype is based on the midpoint of sleep on free days (MSF, i.e. sleep without social obligations). Because most chronotypes tend to accumulate a sleep debt on work days, which is compensated for on free days [3], MSF is adjusted for individual average sleep need (MSF_{sc}; see Supplemental data). Figure 1B shows the distribution of chronotypes (MSF_{sc}) in our database ($N \approx 25{,}000$; mainly from Germany and Switzerland).

The chronotype depends on genetic [4,5] and environmental factors [3] but also on age [3,6–9]. Within each age group, the distribution is very similar to that of the general population (Figure 1B); the respective means, however, vary systematically (Figure 1C). Children are early chronotypes and become progressively later (delaying) during development, reaching a maximum in their 'lateness' at around the age of 20. After 20, they become earlier again (advancing) with increasing age.

The general tendency of females to develop earlier than males is also seen in chronotype (Figure 1D), where young women are already more delayed than young men, and women reach their maximum in lateness earlier (19.5 y). Men continue to delay their sleep until around the age of 21 (20.9 y) and are, on average, later chronotypes for most of their adulthood (see also [10]). This sex (and/or gender) difference disappears at around the age of 50, which coincides with the average age of menopause [11,12]. As subjects become elderly (> 65 y), the data points show a large scatter. This could be due to a combination of low number, less regular social and light schedules, or a less robust circadian system in old age [13–15].

Together with the significant sex/gender differences between puberty and menopause, the systematic changes of chronotype with age indicate — directly or indirectly — the involvement of endocrine factors [6,16]. Thus, incorporation of hormonal aspects could enhance the description and understanding of the circadian phenotype. Concentration and timing of release of many hormones are age dependent [17]. In young people (16–25 y), the time-of-day dependent secretion of growth hormone reaches its maximum (and cortisol, its minimum) at around 1 a.m. — approximately one hour later than in the elderly (> 70 y). The structure of sleep changes along with these endocrine changes [17,18].

The sharp maximum of lateness in chronotype at around the age of 20 coincides with the suggested end of adolescence [1]. Accordingly, one could define when individuals enter adulthood as the age at which their chronotype stops delaying and starts advancing.

Since chronotype is partly controlled by genetic factors, an individual is likely to retain his/her chronotype — in relationship to others of the same age and sex — throughout life. This cross-sectional study cannot distinguish whether individuals become earlier chronotypes with age or whether chronotypes (independent of age) have become later over the last decades. To distinguish between these possibilities, the MCTQ asks for self-assessment of present, childhood, and teenage chronotype (giving a choice of seven categories, ranging from extreme early to extreme late). All self-assessments highly correlate with MSF_{sc}. With progressing age, subjects remember themselves to have been relatively more delayed as teenagers and less advanced as children, compared to their present chronotype. Thereby, they mimick the age-dependent progression of chronotype (Figure 1C,D). This indicates that a subject retains his/her relative position within the distribution throughout life and that the pattern of the age-dependent individual chronotype changes was similar over the last 70 years.

Our data also cannot formally rule out behavioral and environmental factors influencing the age- and sex-dependent differences in chronotype; i.e. do teenagers sleep late because they go to the disco or do they go to the disco because they cannot sleep until late? This can also be followed up in subsequent studies, but if lifestyle were the driving force, a different kinetic would be

predicted (stabilization to a given chronotype by about 30 y). In a parallel study, we collected chronotype information (MCTQ) in three secluded valleys of South Tyrol ($N \approx 800$). The age-dependent progression of chronotype in these genetically well-defined and sociologically distinct areas is practically identical to the one shown here (data not shown), suggesting that age dependency is not specific for the collective of our main database and is present in two populations with very different lifestyles. We therefore propose that the turn of MSF_{sc} from steadily increasing to steadily decreasing with age may represent a biological marker for the end of adolescence.

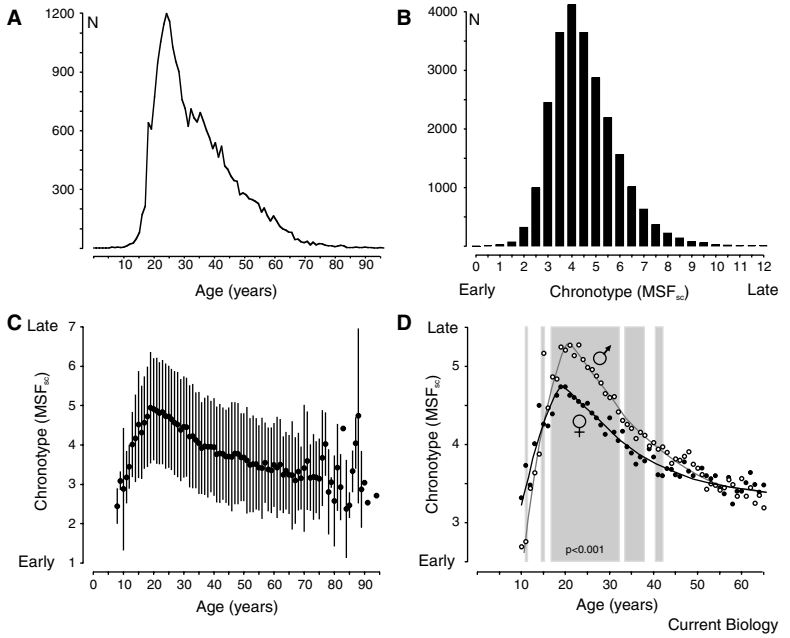

Figure 1. Assessment of chronotype using the MCTQ database (N≈25,000). (A) Age distribution within the database. (B) Distribution of chronotypes. (C) Age-dependent changes in average chronotype (±SD) are highly systematic (except for the age groups of 19, 21, 22, and 23, all other age-dependent averages ± SD are significantly different from that of age group 20; t-test, $p < 0.001$). (D) Age-dependent changes of chronotype are different for males and females (filled circles and black line: females; open circles and gray line: males). Gray areas indicate significant male–female differences (t-test, $p < 0.001$).

Supplemental data

Supplemental data are available at http://www.current-biology.com/cgi/content/full/14/24/R1038/DC1/

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