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Original Article

# Sleep-wake misperception. A comprehensive analysis of a large sleep lab cohort

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ABSTRACT

*Objectives:* Sleep-wake misperception has mainly been reported in insomnia patients. Conversely, the present study aimed to assess the prevalence and correlates of sleep-wake misperception in a large cohort of patients with various sleep-wake disorders, all diagnosed along the third version of the International Classification of Sleep Disorders.

*Methods:* We retrospectively included 2738 patients examined by polysomnography, who in addition estimated upon awakening their total sleep time, sleep onset latency and Wake after sleep onset (WASO). We computed subjective-objective mismatch by the formula (subjective − objective value)/objective value ×100; negative and positive values indicated under- and overestimation, respectively.

*Results:* In the entire sample, the magnitude of under- and overestimation of total sleep time was similar, but varied significantly between diagnostic groups, with insomnia and insufficient sleep syndrome showing the most pronounced underestimation and REM parasomnia and circadian rhythm disorders showing the most pronounced overestimation of total sleep time. In all diagnostic categories, a majority tended to overestimate their sleep onset latency and to underestimate the amount of WASO. Younger age was independently correlated with underestimation of total sleep time and WASO, and with overestimation of sleep onset latency. Overestimation of sleep onset latency independently correlated to an increased latency to N3 sleep stage on polysomnography.

*Conclusions:* While sleep-wake misperception is highly prevalent in all sleep-wake disorders, significant differences exist in magnitude of under- and overestimation between distinct diagnostic groups.



## 1. Introduction

Since almost half a century, sleep researchers have noted a substantial discrepancy between subjective sleep/wake estimations and sleep laboratory findings [1–3]. Underestimation of one's sleep duration appeared to be particularly common in patients suffering from insomnia, including cases of subjective total insomnia [4]. The observation of largely reduced subjective sleep perception despite normal or only mildly disturbed sleep led to the proposition of a new diagnostic term, sleep state misperception, and of a new insomnia subcategory, paradoxical insomnia [5].

Sleep-wake misperception is, however, not limited to insomnia, but has been reported for other sleep disorders, including sleep apnea [6–10], periodic limb movement disorder [11], post-traumatic sleep-wake disturbances [12], and sleep restriction [13]. In addition, sleep disorders rarely manifest as purely isolated entities, but often overlap and coexist with other sleep disorders, eg, comorbidity of insomnia and sleep apnea [14–19]. In the case of narcolepsy, several sleep disorders may co-occur in the same patient (eg, insomnia, sleep apnea, sleep paralysis, rapid eye movement (REM) sleep behavior disorder).

Eventually, it also became clear that sleep state misperception not only involves underestimation but also overestimation of sleep [20,21]. Despite considerable efforts to understand the underlying mechanisms contributing to sleep state misperception, and the

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awareness of the high distress it exerts on affected patients [22], the prevalence, magnitude and types of sleep-wake misperception remains unknown in many sleep-wake disorders. A recent study, however, identified the type of sleep disorder as the most significant predictor of the subjective-objective discrepancy in total sleep time [23]. Overall, subjective-objective discrepancy of sleep-wake variables has rarely been examined in a large sleep laboratory cohort that included careful diagnostic ascertainment along the third version of the International Classification of Sleep Disorders (ICSD-3) [24].

Hence, the goal of the present study was to explore prevalence, severity and correlates of sleep-wake misperception in a cohort of 2738 consecutive patients with various ICSD-3-based sleep disorders, referred for whole-night PSG to a single, tertiary sleep laboratory.

## 2. Methods

The study was conducted at the Department of Neurology, University Hospital Zurich, Switzerland, between June 2017 and February 2020. The Ethics Committee of the Canton of Zurich approved the study protocol (KEK-ZH-Nr 2017−01323). The study was carried out in accordance with the Declaration of Helsinki.

### 2.1. Participants

We retrospectively identified 3303 patients, who underwent diagnostic PSG in the sleep laboratory of the Department of Neurology between October 2002 and July 2017. If patients had multiple PSGs during this period, only the first examination was included in the present analysis. Upon awakening after PSG, patients were asked to estimate their total sleep time (TST), sleep onset latency (SOL), and duration of Wake after sleep onset (WASO). We excluded patients without any subjective estimation of the PSG night, but included all patients who completed the questions on subjective estimation at least partially. Eventually, we included 2738 patients for the final analysis.

Most studies on subjective-objective mismatch of sleep-wake patterns have been done in patients with insomnia, mainly to address the phenomenon of paradoxical insomnia. While these studies often included only PSGs with total sleep time >6.5 h or sleep efficiency >85%, the aim of the present study was to gain a general understanding of the subjective-objective mismatch of sleep-wake patterns across all patients receiving a diagnostic PSG. Therefore, we did not apply a minimally required total sleep time on PSG as inclusion criterion.

For the diagnostic process, we ascertained informations obtained by structured medical history, clinical examination, detailed sleep questionnaires and objective sleep examinations that included at least 2-week actigraphy and in-lab whole-night PSG. In most cases, the patients had a first clinical visit prior and a second clinical visit after the sleep lab examinations. We critically reviewed all diagnoses and, if necessary, revised and adapted them according to the revised ICSD-3 criteria [24]. Many patients received multiple sleep diagnoses; in this case, we used the sleep diagnosis felt to be the clinically most significant for the patient. In our patient cohort, we diagnosed 69 distinct sleep disorders, i.e. most of the 83 sleep disorders presented in the ICSD-3 booklet. Next, we divided the patients into 11 main categories: insomnia (n = 294), sleep-disordered breathing (n = 504), narcolepsy (n = 70), hypersomnia (n = 165), insufficient sleep syndrome (n = 243), circadian rhythm disorders (n = 32), daytime sleepiness/tiredness (n = 238), NREM parasomnia (n = 92), REM parasomnia (n = 446), restless-legs syndrom (RLS) − periodic leg movements during sleep (PLMS) (n = 344), and other (n = 310). While many of our diagnostic groups followed the seven major diagnostic categories proposed by the ICSD-3, some deviations in the present study are noteworthy. Due to a long-lasting interest of our clinic in Central Disorders of Hypersomnolence (CDHS), we subdivided CDHS patients into those with narcolepsy, hypersomnia, and insufficient sleep syndrome. We also subdivided the Parasomnia category into NREM and REM parasomnias, considering the salient clinical differences between mostly healthy young patients with NREM parasomnias and mostly elderly and disabled patients with REM parasomnia (often in the context of a neurodegenerative disorder).

As our sleep laboratory is located within a neurological department, a substantial number of patients had neurological comorbidities (n = 854, 31.2%), mostly neurodegenerative disorders such as Parkinson Disease. Neurological comorbidities were not considered as exclusion criterion. On the other hand, the study did not include healthy subjects, i.e. subjects without sleep pathology, which is unfortunate, as they would have represented an interesting control group.

### 2.2. Subjective estimation, calculation of subjective-objective mismatch, definition of mismatch severity

Based on the subjective estimation of the above-mentioned sleep-wake pattern and the corresponding objective measures obtained by PSG, we calculated an absolute and a relative subjective-objective mismatch. Absolute mismatch was expressed in minutes as the difference between subjective and objective values of TST, SOL and WASO.

We computed the relative mismatch by the following formula: (subjective − objective value)/objective value ×100, in line with previous studies [11,25,26]. A relative mismatch of 0% represents, thus, perfect subjective estimation. Theoretically, the range of relative mismatch extends from −100% (maximal subjective underestimation) to ∞ (large overestimation). >100% overestimation occurred, if the subjectively estimated value was >2times larger than the objective value. This happened rarely in the case of TST, but quite often with SOL and WASO. To avoid excessively large values for overestimation, we trimmed the upper limit to 100% for TST, and to 500% for SO and WASO. For the purpose of the present study, we categorized a relative mismatch from −10% to 10% as accurate estimation, from −10% to −30% as mild underestimation, from −30% to −50% as moderate underestimation, from −50% to −100% as severe underestimation, from 10% to 30% as mild overestimation, from 30% to 50% as moderate overestimation, and >50% as severe overestimation.

### 2.3. Polysomnography

All patients had in-lab overnight PSG recordings, using a multichannel recording system (Embla, RemLogic™). We performed the PSG recordings according to standard practice parameters, and we visually scored sleep stages and associated motor and respiratory events along the most recent standardized criteria [27]. The duration of the PSG recordings varied between 6 and 8 h; we did not include ad libitum PSGs. We ascertained a wide range of neurophysiologic variables, including total recording time (from lights out until lights on), TST, WASO, SOL, sleep latencies to and percentages of sleep stages N1, N2, N3, R, as well as PLMS and apnea-hypopnea-index (AHI). Sleep onset on PSG was defined as the first occurrence of consolidated sleep, either three epochs of uninterrupted N1 sleep stage or occurrence of the first epoch of N2 sleep stage.

A large majority of patients were drug-naïve during their diagnostic sleep examinations. Specific treatment of sleep complaints has either not yet been started or has been interrupted 3 weeks

prior to the sleep examinations. If this was not feasible (eg, antidepressant treatment in patients with depression or dopaminergic treatment in Parkinson's disease patients), pharmacological treatment was continued during PSG.

### 2.4. Statistical analysis

We used SPSS 26 (IBM, Armonk, New York, NY, USA) for statistical analyses. Group data were described by means and standard deviations, or by median and interquartile range (IQR). We used Student's t-test for average comparison of normally distributed data, and Mann–Whitney U-test if data exhibited a non-parametric distribution. For group comparison of nominal data, we used the chi-square test. Dependent on data distribution, we conducted correlation analyses by means of either Pearson's r or Spearman's rho coefficient. To identify independent associates of mismatch severity, we employed stepwise multiple regression analyses with inclusion of the following potential predictor variables: age, sex, body-mass-index, neurological comorbidity, and several PSG variables (total sleep time, sleep latencies to and percentages spent in N1, N2, N3, and R sleep stages, WASO, AHI, PLMS, and arousal index). Significance was accepted at $p < 0.05$.

## 3. Results

### 3.1. Frequency and magnitude of sleep-wake misperceptions

Table 1 shows the main demographic, clinical and PSG parameters of the total sample (n = 2738) and of the main diagnostic categories. Patients underestimated their TST in average by 13 ± 94min. The variability of TST misperception ranged from extreme underestimation by 472min to extreme overestimation by 480min. Mean relative subjective-objective mismatch of TST was −2.1 ± 30.7%. Accurate TST perception was observed in 1016 patients (37.1%), mild-moderate underestimation in 720 patients (27%), severe underestimation in 162 patients (5.9%), mild-moderate overestimation in 637 patients (23.3%), and severe overestimation in 129 patients (4.7%). Seventy-four patients (2.7%) did not estimate their TST. Fig. 1 displays the frequency distribution of distinct relative subjective-objective mismatch categories for TST.

Conversely, the patients overestimated their SOL in average by 22 ± 56min (range: underestimation by 232min to overestimation by 493min). Median relative subjective-objective mismatch of SOL was 83% (IQR: −3.3 – 275%). Accurate SOL perception was observed in only 177 patients (6.5%), mild-moderate underestimation in 364 patients (13.3%), severe underestimation in 248 patients (9.1%), mild-moderate overestimation in 329 patients (12.0%), and severe overestimation in 1560 patients (57.0%). Sixty patients (2.2%) did not estimate their SOL.

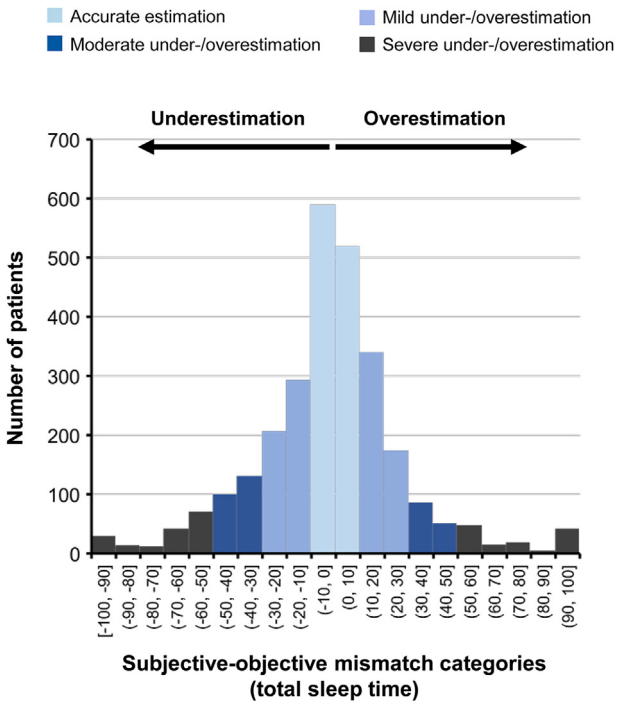


**Fig. 1.** Frequency histograms of subjective misperception of total sleep time in the entire study cohort. Negative and positive values indicate under- and overestimation of total sleep time, respectively. Note that the under- and overestimation of the total sleep time are similar in frequency and severity.

Patients underestimated their WASO in average by 20 ± 66min (range: underestimation by 356min to overestimation by 291min). Mean relative subjective-objective mismatch of WASO was −2 ± 136%. Accurate WASO perception was observed in only 177 patients (6.5%), mild-moderate underestimation in 441 patients (15.1%), severe underestimation in 872 patients (31.8%), mild-moderate overestimation in 208 patients (7.6%), and severe overestimation in 485 patients (17.7%). In addition, 432 patients (15.8%) had a total subjective lack of WASO. One-hundred-twenty-three patients (4.5%) did not estimate their WASO.

**Table 1**
Main demographic, clinical and polysomnography parameters of the total sample and of the main diagnostic categories. In addition, the frequency of patients with a neurological comorbidity is indicated for the entire sample and each diagnostic category.

| | **Age** [y] | **Female sex** (%) | **BMI** [kg/m$^2$] | **Neurological comorbidity** n (%) | **TRT** [min] | **TST** [min] | **SOL** [min] | **WASO** [min] |
|---|---|---|---|---|---|---|---|---|
| Total sample (n = 2738) | 51 ± 17 | 1020 (37%) | 26.2 ± 5.4 | 854 (31.2%) | 439 ± 38 | 347 ± 75 | 24 ± 31 | 68 ± 59 |
| Insomnia (n = 294) | 48 ± 15 | 149 (51%) | 25.7 ± 5.4 | 45 (15.3%) | 437 ± 37 | 323 ± 83 | 36 ± 42 | 78 ± 63 |
| Sleep-disordered breathing (n = 504) | 56 ± 14 | 99 (20%) | 29.8 ± 5.7 | 108 (21.4%) | 442 ± 36 | 351 ± 68 | 21 ± 26 | 70 ± 56 |
| Narcolepsy (n = 70) | 41 ± 18 | 31 (44%) | 25.2 ± 6.3 | 2 (2.9%) | 442 ± 39 | 377 ± 59 | 6 ± 7 | 59 ± 50 |
| Hypersomnia (n = 165) | 41 ± 16 | 73 (44%) | 24.9 ± 5.2 | 32 (19.4%) | 453 ± 34 | 386 ± 68 | 19 ± 20 | 43 ± 49 |
| Insufficient sleep syndrome (n = 243) | 39 ± 14 | 80 (33%) | 25.8 ± 5.1 | 17 (7.0%) | 435 ± 34 | 394 ± 54 | 10 ± 11 | 31 ± 41 |
| Circadian rhythm disorders (n = 32) | 37 ± 14 | 10 (31%) | 26.4 ± 5.7 | 1 (3.1%) | 435 ± 38 | 338 ± 94 | 37 ± 67 | 60 ± 72 |
| Daytime sleepiness, fatigue (n = 238) | 42 ± 15 | 118 (50%) | 25.0 ± 4.9 | 28 (11.8%) | 449 ± 34 | 372 ± 66 | 24 ± 24 | 53 ± 49 |
| NREM parasomnia (n = 92) | 35 ± 12 | 39 (42%) | 25.3 ± 5.8 | 9 (9.8%) | 428 ± 32 | 361 ± 57 | 20 ± 20 | 47 ± 45 |
| REM parasomnia (n = 446) | 63 ± 12 | 160 (36%) | 25.1 ± 4.2 | 389 (87.2%) | 436 ± 37 | 320 ± 72 | 24 ± 28 | 92 ± 63 |
| Restless-legs syndrome/PLMS (n = 344) | 57 ± 16 | 147 (43%) | 25.8 ± 5.1 | 88 (25.6%) | 438 ± 40 | 325 ± 82 | 31 ± 41 | 82 ± 63 |
| Others (n = 310) | 50 ± 16 | 114 (37%) | 25.4 ± 4.8 | 135 (43.5%) | 437 ± 43 | 345 ± 73 | 26 ± 31 | 67 ± 53 |

BMI – body mass index; NREM – non rapid eye movement; REM – rapid eye movements; PLMS – periodic leg movements during sleep; TRT – total recording time; TST – total sleep time; SOL – sleep onset latency; WASO – Wake after sleep onset.

### 3.2. Differences in subjective-objective mismatch between diagnostic categories

The descriptive statistics of subjective-objective mismatch in distinct diagnostic categories as well as the distribution of mismatch severity within and between these diagnostic categories are summarized in Table 2 and Fig. 2.

In the entire study cohort, the correlations between subjective and objective values of TST, WASO and SOL were similar (Fig. 3A). The different diagnosis-specific correlations between subjective and objective TST, WASO and SOL are depicted in Fig. 3B.

Accurate TST perception varied between different diagnostic categories from 31.8% to 54.4%. The percentage of patients with accurate TST perception was highest in NT (54.4%) and

**Table 2**
Overview on relative and absolute mismatch between polysomnographic findings and subjective estimation of total sleep time, sleep onset and wake after sleep onset in different sleep-wake categories.

| | Total sleep time | | Sleep onset latency | | Wake after sleep onset | |
|---|---|---|---|---|---|---|
| | Relative Mismatch [%] | Absolute Mismatch [min] | Relative Mismatch [%] | Absolute Mismatch [min] | Relative Mismatch [%] | Absolute Mismatch [min] |
| Total sample | −2 ± 31 | −13 ± 94 | 150 ± 192 | 22 ± 56 | −2 ± 136 | −20 ± 66 |
| Insomnia | −12 ± 34 | −48 ± 102 | 163 ± 189 | 38 ± 77 | 38 ± 164 | −3 ± 77 |
| Sleep-disordered breathing | −2 ± 30 | −12 ± 94 | 157 ± 194 | 21 ± 51 | −14 ± 120 | −25 ± 67 |
| Narcolepsy | −2 ± 25 | −12 ± 94 | 296 ± 204 | 20 ± 33 | 36 ± 172 | −7 ± 70 |
| Hypersomnia | −1 ± 26 | −4 ± 97 | 116 ± 185 | 12 ± 32 | −5 ± 141 | −10 ± 55 |
| Insufficient sleep syndrome | −7 ± 23 | −27 ± 86 | 195 ± 197 | 20 ± 40 | 45 ± 184 | 2 ± 52 |
| Circadian rhythm disorders | 5 ± 35 | −2 ± 106 | 84 ± 128 | 4 ± 25 | 40 ± 184 | 2 ± 55 |
| Daytime sleepiness, fatigue | −3 ± 29 | −16 ± 95 | 132 ± 180 | 24 ± 55 | −11 ± 124 | −16 ± 54 |
| NREM parasomnia | −2 ± 23 | −12 ± 71 | 150 ± 177 | 21 ± 40 | 2 ± 139 | −11 ± 40 |
| REM parasomnia | 5 ± 39 | 10 ± 92 | 124 ± 186 | 17 ± 55 | −24 ± 109 | −37 ± 71 |
| Restless-legs syndrome/PLMS | −3 ± 34 | −13 ± 93 | 167 ± 201 | 31 ± 70 | −15 ± 117 | −29 ± 71 |
| Others | 0.3 ± 28 | −4 ± 89 | 111 ± 179 | 16 ± 51 | −15 ± 113 | −23 ± 60 |

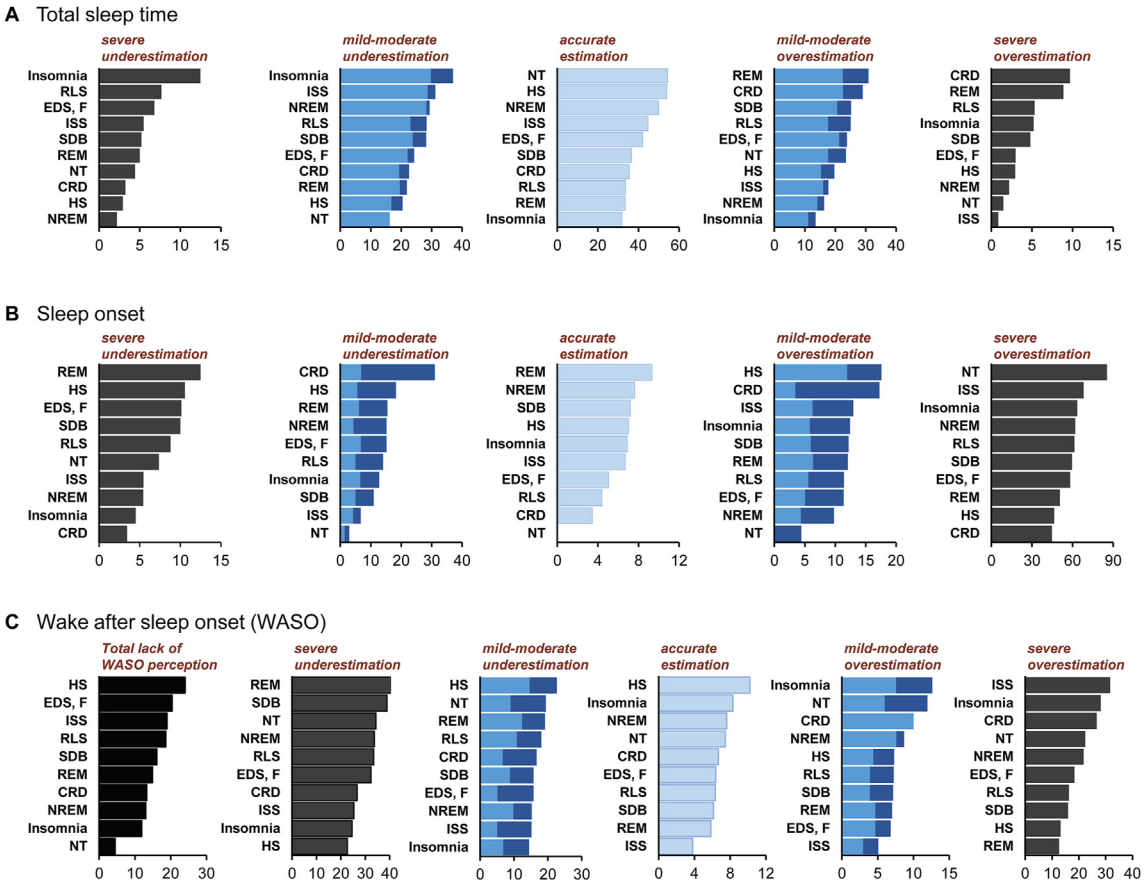


**Fig. 2.** Comparison of different degrees in subjective-objective mismatch of total sleep time (A), sleep onset latency (B), and wake after sleep onset (C) between distinct sleep-wake categories. In the combined group with mild-moderate under-/overestimation, light-blue indicates mild and dark-blue indicates moderate under-/overestimation. Abbreviations: CRD - circadian rhythm disorders; EDS – excessive daytime sleepiness; F – Fatigue; HS – hypersomnia; ISS – insufficient sleep syndrome; NREM – NREM parasomnia; NT – narcolepsy; REM – REM parasomnia; RLS – restless legs syndrome; SDB – sleep-disordered breathing. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

hypersomnia (54.0%), and lowest in insomnia (31.8%) and REM sleep parasomnia (33.4%). For SOL, accurate perception varied from 0% to 9.3%, being highest in REM parasomnia (9.3%) and NREM parasomnia (7.6%), and lowest in narcolepsy (0%) and circadian rhythm disorders (3.5%). For WASO, accurate perception varied from 3.8% to 10.2%, being highest in hypersomnia (10.2%) and insomnia (8.3%), and lowest in insufficient sleep syndrome (3.8%) and REM parasomnia (5.8%). As depicted in Fig. 4, the distribution of patients, who either under- or overestimated their TST, their WASO, and their SOL, differed between groups.

### 3.3. Correlates of sleep-wake misperception

In multiple linear regression models, underestimation of TST appeared to be independently correlated with higher TST on PSG (beta = 0.260, t = 13.132, $p < 0.001$), younger age (beta = 0.066, t = 3.268, $p = 0.003$) and higher body mass index (beta = 0.051, t = 2.753, $p = 0.006$). Likewise, underestimation of WASO appeared to be independently correlated with increased WASO on PSG (beta = 0.261, t = 8.665, $p < 0.001$) and younger age (beta = 0.144, t = 6.984, $p < 0.001$). Finally, overestimation of SOL was independently correlated with decreased sleep onset on PSG (beta = 0.484, t = 22.284, $p < 0.001$), increased latency to N3 sleep stage (beta = 0.209, t = 9.548, $p < 0.001$) and younger age (beta = 0.053, t = 2.940, $p = 0.003$).

Age also affected several polysomnographic variables: age correlated negatively with TST (r = −0.36, $p < 0.001$) and positively with WASO (rho = 0.48, $p < 0.001$).

In patients with sleep-disordered breathing, apnea-hypopnea-index (AHI) did not appear to correlate with any variable of relative misestimation. Likewise, in RLS/PLMS patients, there was no correlation between PLMS index and relative SOL or WASO misestimation; only the relative TST misestimation correlated mildly with PLMS index (r = 0.16, $p = 0.03$).

## 4. Discussion

The present study provides data on frequency, magnitude and correlates of subjective-objective mismatch of sleep-wake variables in a large sample of patients with different sleep diagnoses according to ICSD-3 criteria. While previous studies on subjective-objective mismatch of nocturnal sleep parameters have largely focused on insomnia patients and particularly on paradoxical insomnia, our results now demonstrate that inaccurate sleep-wake estimation represents a common feature throughout all sleep-wake diagnoses. Moreover, we found that sleep-wake misperception involves in similar measure both under- and overestimation of total sleep time, but the ratio between under- and overestimation differed between sleep diagnoses, with the strongest percentage of underestimation in insomnia. Longer total sleep times and longer WASO predispose to their subjective underestimation, while a shorter sleep onset latency contributes to its subjective overestimation. Overall, as pathological self-reported sleep-wake estimates shape sleep physicians' decisions of appropriate diagnostic examinations, the frequent discrepancy with objective PSG findings is a reminder to clinicians that execution of the latter is helpful not

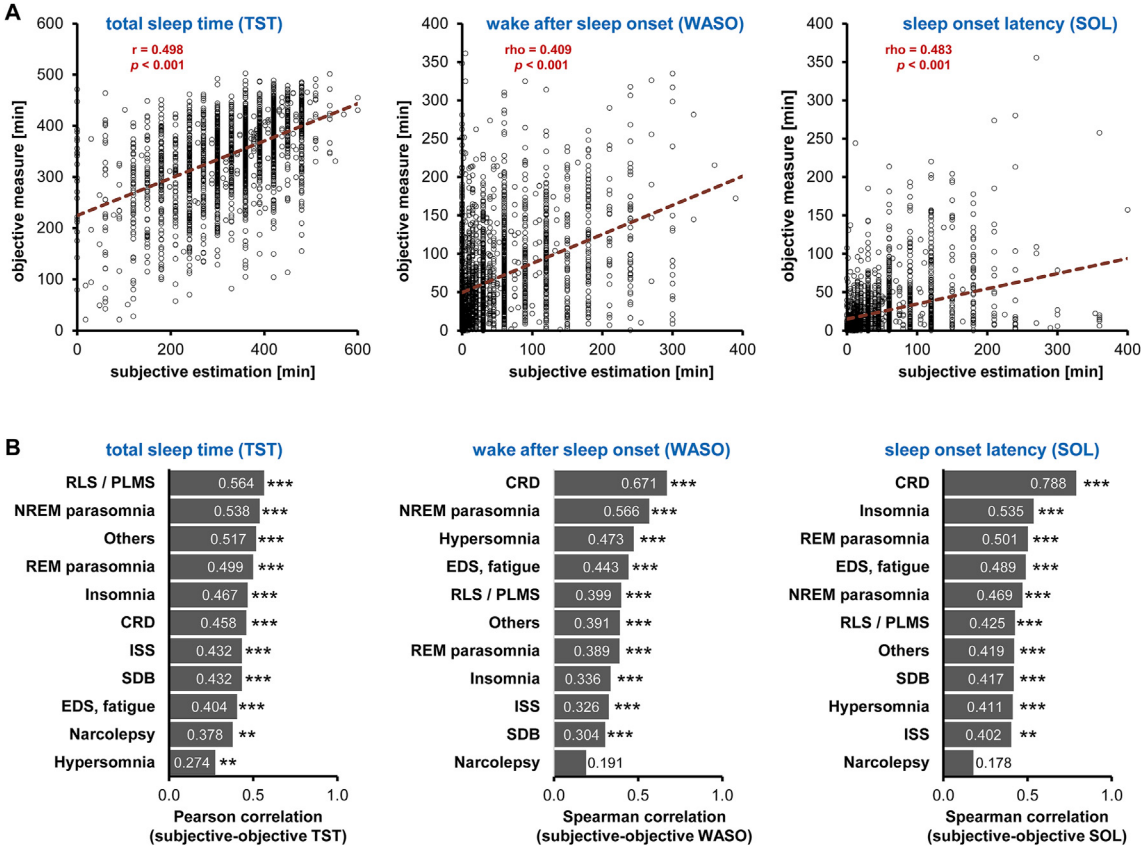


**Fig. 3.** Scatter plot showing the correlations between subjective and objective total sleep time (TST), wake after sleep onset (WASO), and sleep onset latency (SOL) (A). The correlation strengths between subjective and objective TST, WASO, and SOL were differentially distributed between distinct sleep-wake categories (B).; Abbreviations: CRD - circadian rhythm disorders; EDS – excessive daytime sleepiness; ISS – insufficient sleep syndrome; RLS/PLMS – restless legs syndrome and/or periodic leg movements during sleep; SDB – sleep-disordered breathing.

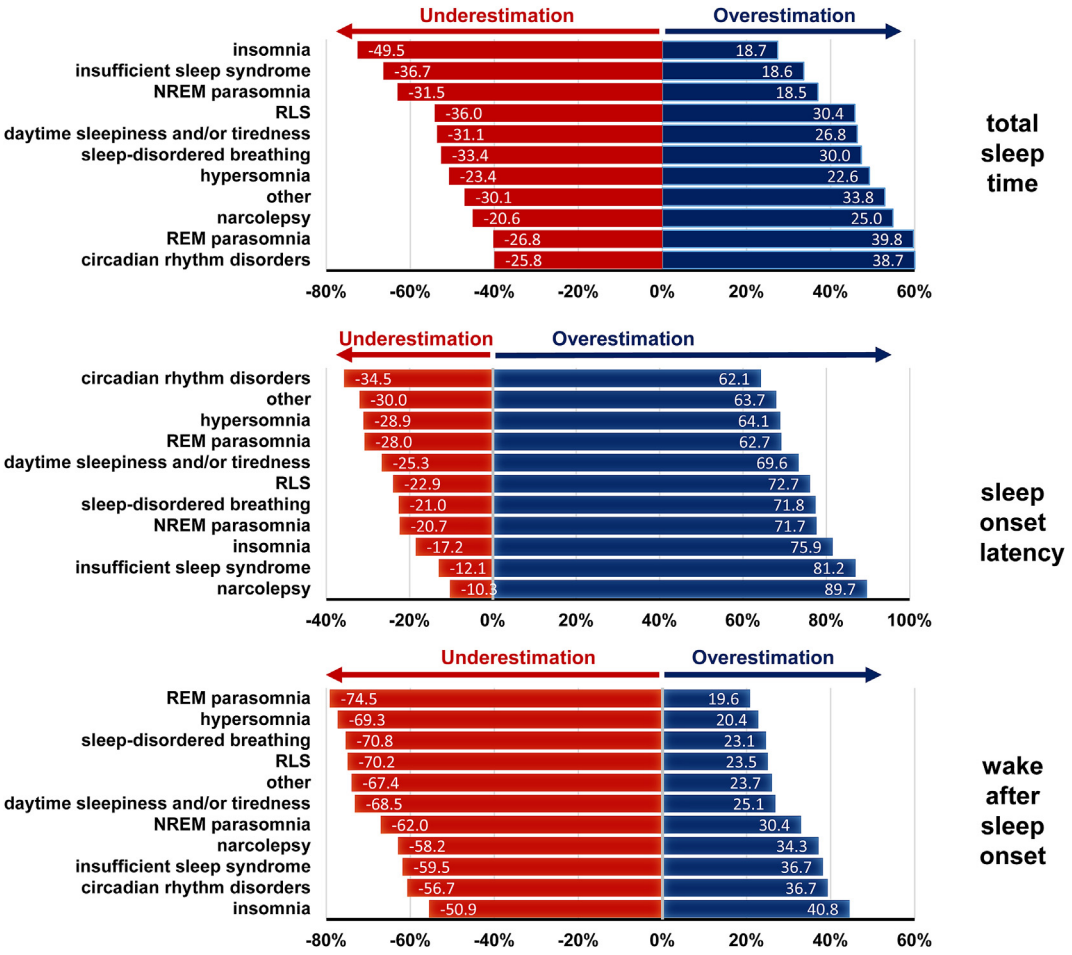


**Fig. 4.** Patients with distinct sleep categories are dichotomized in those who under- and overestimated total sleep time, sleep onset latency, and wake after sleep onset. The sleep-wake categories are arranged by the frequency distribution of under- and overestimation.

only to confirm patients' complaints, but also to identify distorted subjective sleep-wake perceptions.

The entire patient cohort was similarly likely to underestimate total sleep time than to overestimate it, as already shown by previous work [11]. Overall, the 2738 patients showed a distribution in their mismatch severity between subjective and objective total sleep time that resembled a Gaussian distribution. However, the ratio between under- and overestimation of total sleep time varied significantly between diagnoses, ranging from 2.6:1 in patients with insomnia to 1:1.4 in patients with circadian rhythm disorders or REM parasomnia. While confirming that subjective underestimation of total sleep time is characteristic for insomnia and more pronounced than in other sleep diagnoses, our study demonstrates at the same time that large subjective-objective mismatch of total sleep time is by no means unique to patients suffering from insomnia.

Regarding sleep onset latency, subjective overestimation appeared to be far more common than underestimation, a finding already reported by previous studies, mainly in insomnia patients [1,11,28]. Interestingly, the magnitude of sleep onset overestimation was largest in patients with narcolepsy and insufficient sleep syndrome, i.e. in patients with particularly short sleep latency, directly followed, however, by patients with insomnia. This suggests that different factors contribute to sleep onset overestimation. On one hand, the use of relative subjective-objective mismatch of sleep onset latency may not be appropriate in patients with short sleep onset, as indicated by the fact that a subjective-objective mismatch of 4min vs. 2min (i.e., absolute mismatch of only 2min) results in the same 100% overestimation than a mismatch of 4 h vs. 2 h (i.e., absolute mismatch of 2 h). The particularly strong independent correlation between sleep onset latency overestimation and short sleep latency points in the same direction. On the other hand, the insomnia group also exhibited a marked sleep onset latency overestimation, although their sleep latency was longer than in most other diagnostic groups. Specific personality traits and psychological comorbidities [29], which unfortunately have not been systematically determined in the present patient cohort, may account for the more pronounced sleep onset latency overestimation, and generally for the more inaccurate sleep-wake estimation in patients with insomnia. Finally, sleep onset latency on polysomnography is defined as the first occurrence of consolidated sleep, either three epochs of uninterrupted N1 sleep stage or occurrence of the first epoch of N2 sleep stage, but the subjective perception of falling asleep may not coincide with this definition. Indeed, 60% of normal sleepers did not realize they had fallen asleep when awakened 4–8min after the occurrence of the first sleep spindles [30]. This may explain why a longer latency to N3 sleep correlated with a larger overestimation of sleep onset latency. It is not uncommon that patients quickly enter N1 and N2 sleep stages, but then fail getting consolidated deep sleep but instead fluctuate between awakenings and light sleep stages. Many of these patients will perceive

the delayed occurrence of N3 sleep as sleep onset, instead of the earlier occurrence of N1/N2 sleep stages.

We anticipated that subjective underestimation of total sleep time is paralleled by an overestimation of the amount of WASO. Intriguingly, we found a predominance of WASO underestimation across all diagnostic categories. While it is well known that short arousals are typically not recalled, the marked underestimation of even longer wake bouts was surprising. Even patients suffering from insomnia were more likely to underestimate than overestimate the amount of WASO, although the ratio between under- and overestimation was smallest compared to all other diagnostic categories. It seems that the perspective on wakefulness affects the direction of the mismatch: wakefulness during the transition from wake to sleep at the beginning of the night might be stronger perceived than the reemergence of wakefulness from sleep during the night, contributing to a subjective overestimation of sleep onset latency and an underestimation of WASO. Bianchi and colleagues recently noted this context dependency of wake (mis-) perception in patients with insomnia and sleep apnea [7].

Younger age appeared as an independent risk factor for a stronger underestimation of total sleep time and WASO as well as for a stronger overestimation of sleep onset latency. This effect of age on subjective sleep-wake misperception has not yet been reported in the literature. Several reasons might account for this finding. Younger people are facing challenges in both work and private life and may, thus, react more emotionally to disturbed sleep. Fear of reduced functioning during daytime likely enhances their perception of nocturnal wakefulness, making them more prone to underestimation of total sleep time and overestimation of WASO. On the other hand, increasing age is associated with shorter total sleep time and more WASO, thus reducing the risk of underestimation of total sleep time and overestimation of WASO.

The large sample size and the careful diagnostic assessment according to ICSD-3 criteria belong to the main strengths of the present study. Several limitations have to be acknowledged as well. First, sleep quality affects the accuracy of subjective sleep-wake estimation, and night-to-night variability may differ across diagnostic categories. Thus, first-night effect and night-to-night variability likely affected the accuracy of subjective sleep estimation, but have not been controlled in the present study. Second, the division in diagnostic subgroups did not exactly follow the main categories of the ICSD-3 classification, but reflected to some extent the clinical focus in our sleep clinic, for instance the subdivision of Central Disorders of Hypersomnolence into narcolepsy, hypersomnia and insufficient sleep syndrome. Third, as already mentioned, there is a lack of psychological characterization and assessment of comorbidities such as nocturia or nocturnal pain, which could have provided important insight into the underlying causes of subjective sleep-wake misestimating. Fourth, a minority of patients kept taking their usual medications during PSG, but the potential impact on subjective sleep-wake perception of certain drugs (eg, antidepressants) has not been specifically accounted for. Finally, the patient cohort comprised a substantial number of patients with comorbid neurological disorders. A bidirectional causal relationship exists between sleep disorders and neurological disorders, but the independent contribution of a neurological comorbidity to the magnitude of sleep-wake misperception remains unclear. In Parkinson's disease, for instance, underestimation of daytime naps has been reported [31], but otherwise there is a paucity of data on the impact of neurological comorbidities on sleep-wake misperception.

In conclusion, treating physicians should be aware that sleep-wake misperception is highly prevalent throughout all sleep disorders. Our findings have implications in the clinical management of patients with sleep disorders. While both self-reported sleep patterns and objective sleep disturbances contribute to the clinical importance of sleep disorders, objective evaluation by polysomnography should be pursued more often compared to current clinical practice. The emergence of consumer-based mobile polysomnography systems for multiple, unobtrusive sleep measurements at home and progresses in applying artificial intelligence and machine learning for rapid and automated data analysis are important technological developments that will help overcoming current limitations of polysomnography (i.e. high costs, time-consuming acquisition, restraints from insurances). Our findings also advise caution regarding epidemiologic studies on the relationship between self-reported sleep duration and numerous detrimental health problems.

## CRediT author statement

**Philipp O. Valko**: Conceptualization, Methodology, Formal Analysis, Original Draft, Writing, Supervision, Review & Editing. **Schirin Hunziker**: Formal Analysis, Original Draft, Writing, Review & Editing. **Kevin Graf**: Software, Review & Editing. **Esther Werth**: Review & Editing. **Christian R. Baumann**: Data Curation, Project Administration, Review & Editing.

## Conflict of interest

None declared.

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