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The “morning voice”: The effect of 24 hours of sleep deprivation on vocal parameters of young adults

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RUNNING HEAD: The effect of sleep deprivation on vocal parameters of young adults
Abstract

Fatigue following sleep deprivation adversely affects various aspects of human performance. It also induces recognizable voice changes, but the literature is inconsistent regarding their nature. The current study used acoustical analyses to assess the effect of 24 hours of sleep deprivation on vocal parameters of young adults. Forty-seven participants (23 females, 24 males) were tested after nocturnal sleep and after 24 hours of sleep deprivation. Different voice samples were recorded (sustained phonation, words and sentences) and analyzed for fundamental frequency (F₀, in Hz), vocal intensity (in dB), harmonic-noise ratio (HNR, in dB), jitter and shimmer (in %). The main finding was significantly higher HNR values following sleep deprivation than nocturnal sleep for females, across all voice samples. The HNR is a measure of the degree of acoustic periodicity, or the amount of noise compared to the harmonic quality present in the voice. As its values are higher, the voice quality is perceptually better. The current results indicate that females had a significantly higher ratio of vocal harmonics compared to vocal noise when they were sleep deprived. In contrast, following nocturnal sleep, the ratio of vocal harmonics compared to vocal noise was lower, that means the voice quality was poorer. This may explain the common perceptual impressions of decreased voice quality after sleep, that may be more pronounced in females.

Key words: Sleep deprivation; Fatigue; Acoustical analysis; Voice quality; Harmonics-noise ratio.
1. Introduction

Altered sleep schedules can lead to either partial or total sleep deprivation [1]. Total sleep deprivation refers to an acute situation, in which an individual gets no sleep (e.g., a student who studied all night), while a partial sleep deprivation describes a night of reduced or interrupted sleep (due to sleep disorders, medications, work schedule etc.). The inevitable result of sleep deprivation is a subjective feeling of fatigue. According to Sharpe and Wilks [2], "Fatigue can refer to a subjective symptom of malaise and aversion to activity or to objectively impaired performance.". To better define this term, fatigue can be classified into two main categories, where mental fatigue is believed to be psychological in nature, while physical fatigue refers to muscle fatigue [3]. Note, the causes of fatigue during muscular exercise include brain-related central mechanisms (a decrease in muscle force attributable to a decline in motoneuronal output, central fatigue; [4]), as well as peripheral mechanisms (relate to the muscles themselves, peripheral fatigue; [5]).

The focus of the current study is fatigue due to sleep deprivation. Sleep deprivation has been shown to affect several aspects of human performance (e.g. psychological, cognitive, and motor functions [6, 7, 8, 9]). It has also been found that sleep deprivation may affect various circadian organized parameters, such as body temperature [10, 11] and cortisol excretion [12, 13]. Relatedly, sleep deprivation and fatigue associate with physiological changes (e.g., decreased muscle tension, flat and slow respiration) that can influence voice characteristics [14], the primary concern of the current study.

Subjectively, many people are aware that their voice changes when they are not getting adequate sleep [15]. When an individual is tired (for example, following
sleep deprivation), a spouse or a close friend may comment on the quality of the voice, and remarks such as “you sound croaky” or “rough,” are common [16]. Indeed, the literature indicates that voice is sensitive to fatigue, and that fatigue may produce recognizable voice changes [e.g., 1, 17, 18, 19]. For example, most studies agree that fatigue reduces the *pitch variations*, and that individuals display more monotonic or "flattened voices" after sleep deprivation, resulting in a relatively stable harmonic pattern [18, 20, 21]. There is also general agreement among researchers concerning the effect of fatigue on vocal loudness. Typically, following sleep deprivation (that causes changes in breathing dynamics and muscle tension, similar effect of stress) the voice sounds softer [15, 20, 22]. In line with this rationale, while producing speech sounds that require a large average air flow, voice was found to change in synchrony with both direct measures of fatigue and with changes predicted by the length of time awake [23].

The effect of fatigue on other voice characteristics is less clear with mixed evidence. Take, for example, *voice pitch* (determined by the vibratory frequency of the vocal folds). Whitmore and Fisher [24] suggested that the voice fundamental frequency (F₀) may be a valid indicator of a speaker’s fatigue state and reported that fatigue and workload correlate with lower F₀. Similarly, Krajewski and Kröger [22] posited that decreased muscle tension (which characterizes sleepiness) leads to flat and slow respiration (i.e., reduced subglottal pressure) resulting in lower F₀. In contrast, other researchers have associated physical fatigue and sleep deprivation to higher mean F₀ [15, 16] or failed to detect fatigue-related F₀ changes [25].

Focusing on the relationship between sleep deprivation and voice quality, Bagnall, Dorrian, and Fletcher [16] used listener judges’ ratings, and found that 24 hours of sleep deprivation adversely affected the voices, which were perceived as
rounder, less brilliant and more tired (i.e., sounding “down” or “flat” in terms of the mean F₀). The brilliance of the voice (the perceptual correlate of the singer’s formant, or “ring”, [26]) is the product of muscle contraction involving the larynx and vocal tract. Therefore, it is not surprising that it decreases with fatigue [16]. Similarly, decreased sleep (an average of 6 hours of sleep per night) was associated with the presence of a hoarse voice among teachers [27; For similar pattern of results in the general population, see: 28]. Yet, the precise nature of these vocal quality changes was not defined.

The present study seeks to contribute to the existing literature by further investigation of the effect of 24 hours sleep deprivation on specific objective vocal parameters of young adults, using acoustical analysis. This sleep deprivation period was chosen following Bagnall, Dorrian, and Fletcher [16]. To answer our research question, identifying voice parameters affected by sleep deprivation, the participants were recorded twice (in a random order), after nocturnal sleep or after 24 hours of sleep deprivation. In each session, they were asked to produce several voice samples, and these recordings were acoustically analyzed. Since sleep deprivation leads to fatigue, which relates to reduced muscle tension, flat and slow respiration, and irregular or asynchronous vocal fold vibration [15, 20, 22], we hypothesized that various related basic acoustic parameters (voice intensity, F₀, HNR, jitter and shimmer) will be negatively affected.

Identifying the relationship between fatigue and voice characteristics carries clinical implications, as in recent years the prevalence of fatigue in the general population is high [16]. It was found to be prevalent (about 20%) among adolescents [29] and university students, who typically deal with stressors such as overloaded lessons, long class schedules, and academic performance concerns [30]. Additionally,
many students are involved in term-time employment, and typically work early morning or evening shifts [31]. Availability for evening work is particularly required by the catering and leisure industry, supermarkets and by call centers/ tele-sales enterprises. Given such work hours, fatigue due to sleep deprivation is unavoidable. As voice is an essential aspect of human communication (and may even be a crucial factor for safe and efficient performance), it is important to reveal the relationship between vocal features and sleep deprivation.

2. Method

2.1. Participants.

The study included 47 healthy undergraduate students with no vocal complaints (23 females, mean age: 23 years, age range: 18-25 years, and 24 males, mean age: 24 years, age range: 18-25 years). Recruitment was achieved through advertisement within the university facilities. All participants were native Hebrew speakers, that reported no language or learning difficulties, and no history of neurological or psychiatric diseases. All participants were screened for normal hearing, good sleep quality (using the Pittsburgh Sleep Quality Index [32]), articulation and voice (the full procedure is detailed next). The screening procedure was conducted by two research assistants (RAs), trained speech-language pathology undergraduates. Participants received the equivalent of 80 USD for participation. The study was approved by the University's ethics committee, and all participants signed an informed consent.

2.2. Experimental tools and stimuli.

Screening tests. To select the participants, hearing, voice and speech abilities were assessed using appropriate screening tests. Performing the screening procedure was
important in light of the known associations between these domains [for example, the voices of hearing-impaired individuals typically have a higher F0; see: 33]. The two RAs performed the screening tests. In case of a disagreement between them, the first Author (an experienced SLP) was consulted.

(a) Hearing screening test. Participants were screened for normal hearing on 500, 1000, 2000, and 4000 Hz (< 20 dB), using an AD229B inter-acoustic audiometer.

(b) Articulation screening test. To confirm typical articulation and to verify that no speech difficulties appear, we used a common Hebrew articulation and naming test [34]. The test includes 32 pictures of common objects, mono- to four-syllabic words. All consonants appear in initial-, medial-, and final-positions, and all vowel are also fully represented. Participants were required to name the pictures.

(c) Perceptual evaluation of voice quality. During the participants’ intake and the administration of the articulation test, the RAs performed a perceptual assessment of voice quality using the 4-point Grade (G) parameter of the GRBAS (Grade, Roughness, Breathiness, Asthenia, Strain) scale, a clinician-based voice assessment protocol [35]. Participants were screened for no dysphonia (G = 0).

(d) Evaluation of subjective sleep quality. Subjective sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI; [32]), a self-rating questionnaire comprised of 21 items that assesses sleep quality over a 1-month time interval. It evaluates subjective sleep quality, sleep latency and duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction. Participants were screened for “good” sleep quality (global PSQI score < 5, indicating the absence of sleep disorders).
Actigraphy. Following the screening procedure, participants who were successfully screened were given actigraphs (or actiwatches), to assess their habitual sleep. Actiwatches are wrist watch-like devices that provide accurate estimates of the sleep/wake cycle via movement. Each participant was given a Mini Mitter Actiwatch (model AWLP) to be worn for two periods of three consecutive nights (three nights of habitual sleep pre-study, followed by one night of sleep or sleep deprivation).

Speech stimuli for voice recordings. In each experimental session, at 08:00 a.m. the morning following a night of sleep or sleep deprivation, the participants' voices were recorded. The literature is inconsistent regarding what type of voice sample (e.g., sustained vowels, continuous speech) is most appropriate for acoustic analysis [36]. As some previous studies demonstrated differences in acoustic measures between stimulus types [37], we decided to include different kinds of stimuli in the current voice evaluations.

The participants were recorded producing three types of voice samples: (a) A sustained phonation task – Participants were instructed to sustain the vowel /a/ at a comfortable loudness level and a constant pitch, (b) Words production task – Participants listened to the Hebrew version of the AB words test [38] and were required to repeat each word immediately after hearing it. The test is composed of lists of 10 mono-syllabic Consonant-Vowel-Consonant meaningful words, which are phonemically balanced (i.e., in each list every consonant appears once, and every vowel appears twice). Each participant heard random two lists, and (c) Sentences production task – Participants listened to the Hebrew version of the CUNY topic-related sentence sets [39] and were required to repeat each sentence immediately after
hearing it. The test includes six lists of 12 sentences each, differed with regard to their length (short, and long) and their type (statements, and questions). Each participant heard one list.

The Hebrew version of the AB words and the CUNY topic-related sentences were recorded in a recording studio using a SONTRONICS TCS-6 microphone and Samplitude classic 8.1 recording software. They were edited using the SoundForge program, which digitized (16-bit) at a sampling rate of 44 kHz. These speech stimuli were aurally presented using the Winamp Media Player 5.7 software. Their level was normalized using the overall RMS, and they were presented binaurally at a level of 65 dB HL by the audiometer, via STech supra aural headphones.

The voice samples of the participants (sustained phonation, words and sentences) were recorded using a headset top-quality noise cancellation microphone (Sennheiser PC 363D Gaming Headphones). The use of headset ensured that all participants had the microphone at equal distance of 3 cm from the corner of their mouth, to prevent turbulence due to direct airflow from impinging on the microphone (For a related recording procedure, see: [40]). The audio recordings of the participants' responses were prepared for a later examination and analyses.

2.3. Procedure.

Screening meeting. Seventy-three potential participants who responded to the ads posted on campus were invited to an individual screening session. The RAs provided an explanation of the research and its goals and made sure these candidates met the inclusion criteria by an interview. Appropriate participants signed an informed consent form and performed the hearing screening test and the articulation screening
test (also confirming no dysphonia) and completed the PSQI questionnaire. Twenty-six of the candidates were dismissed either after the screening phase, or because they did not complete both sleep and sleep-deprivation conditions.

The remaining 47 students participated in the experiment. Following the screening procedure, each participant received an actiwatch, and were instructed to wear it for a period of three consecutive nights. The average of these three nights of sleep was analyzed as an indicator of habitual sleep. After this habitual sleep period, participants completed one of the two experimental conditions: (a) the sleep condition, or (b) the sleep deprivation condition, in a counterbalanced order. The other condition was completed at least 1 week later (three consecutive nights of habitual sleep, followed by the experimental condition night).

Sleep condition. Participants were asked to sleep for their habitual sleep duration at home for another consecutive night. Compliance was verified using actigraphy and was full for all participants.

Sleep-deprived condition. The sleep-deprivation manipulation occurred over the course of one in-laboratory night. Participants were invited to the laboratory in groups of three, where they spent the night together with a RA. During the night they could read, watch TV or videos, play box-games (like chess), or study.

Voice recordings. At 08:00 a.m. the morning following the sleep or sleep-deprivation night, each participant visited the laboratory and completed the voice recordings. The tasks were performed in a random order.

A visual depiction of the experimental procedure and study schedule are shown in Figure 1.
2.4. Acoustical analysis.

Upon completion of the study, acoustical analyses of the voice samples were performed using Praat software [41]. Some examples of the voice recordings used are shown in Figure 2. For analyses, a 5-s segment was excerpted from the middle of the sustained vowel, as well as four successive words and a single long sentence from the mid-part of each list [see: 42]. Each voice sample was analyzed (means and SDs) for F₀ (in Hz), voice intensity (in dB), HNR (in dB), jitter and shimmer (%, for sustained phonation). These voice measurements were chosen following Harger's [43] related study. To avoid possible biases, the analyses were conducted by two other trained RAs, who were blinded to the experimental condition.
Figure 2: Examples of the voice recordings used for acoustical analyses: (a) sustained phonation (the vowel /a/), (b) word production, and (c) sentence production.

2.5. Statistical analyses.

Statistical analyses were carried out using SPSS-19 software (SPSS Inc., Chicago, IL). The analysis of the acoustic measures was performed separately for each voice sample (/a/, words, and sentences for each individual and session) using repeated-measures MANOVA with experimental condition (following sleep or sleep deprivation) as a within-participant factor, and voice parameters (F0, voice intensity, HNR, jitter, and shimmer) as dependent variables. Due to a-priori gender differences in voice features, all analyses were carried out separately for female and male participants in a .05 probability level.
3. Results

Table 1 lists the mean values (and SDs) of average fundamental frequency ($F_0$, in Hz), vocal intensity (in dB), HNR (in dB), jitter (in %), and shimmer (in %), for the three voice samples recorded following a night of sleep or a night of sleep deprivation, separately for female (a) and male (b) participants.

The main finding of this study was significantly higher HNR after sleep deprivation than following nocturnal sleep for female participants. This pattern was consistent and was found across all voice samples. The statistical analysis confirmed its significance; for sustained phonation, a mean difference of 1.26 dB, $F(1,21) = 4.67, p = .042, \eta^2_p = .182$; for words, a mean difference of .99 dB, $F(1,21) = 6.22, p = .021, \eta^2_p = .221$; and for sentences, a mean difference of 1.09 dB, $F(1,21) = 10.94, p = .003, \eta^2_p = .332$. See also Table 1a.

Another finding of the current study was significantly lower mean intensity levels following a night of sleep deprivation than following nocturnal sleep, for both female (a mean difference of 1.45 dB, $F(1,22) = 409.99, p < .001, \eta^2_p = .949$) and male participants (a mean difference of 1.32 dB, $F(1,23) = 386.34, p < .001, \eta^2_p = .944$), but only in voice sample of sentences (see Table 1a and 1b).
Table 1: Mean values of acoustic variables measured following a night of sleep or a night of sleep deprivation, and repeated-measures univariate analysis, for all types of voice samples for (a) female and (b) male participants.

(a) Female participants

<table>
<thead>
<tr>
<th>Type of Voice Sample</th>
<th>Voice parameter</th>
<th>After 24 h Sleep Deprivation, Mean (SD)</th>
<th>After Nocturnal Sleep, Mean (SD)</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustained phonation /a/</td>
<td>Mean F&lt;sub&gt;0&lt;/sub&gt; (Hz)</td>
<td>206.29 (17.25)</td>
<td>197.07 (30.68)</td>
<td>3.34</td>
</tr>
<tr>
<td></td>
<td>Mean Intensity (dB)</td>
<td>74.68 (6.94)</td>
<td>74.52 (6.37)</td>
<td>.01</td>
</tr>
<tr>
<td></td>
<td>HNR (dB)</td>
<td>20.60 (4.18)</td>
<td>19.34 (3.06)</td>
<td>4.67*</td>
</tr>
<tr>
<td></td>
<td>Jitter (%)</td>
<td>.43 (.18)</td>
<td>.49 (.17)</td>
<td>2.67</td>
</tr>
<tr>
<td></td>
<td>Simmer (%)</td>
<td>3.07 (1.45)</td>
<td>3.21 (2.01)</td>
<td>.13</td>
</tr>
<tr>
<td>Words</td>
<td>Mean F&lt;sub&gt;0&lt;/sub&gt; (Hz)</td>
<td>208.43 (22.59)</td>
<td>206.02 (19.09)</td>
<td>.33</td>
</tr>
<tr>
<td></td>
<td>Mean Intensity (dB)</td>
<td>69.07 (4.47)</td>
<td>70.28 (5.31)</td>
<td>.72</td>
</tr>
<tr>
<td></td>
<td>HNR (dB)</td>
<td>11.79 (2.51)</td>
<td>10.80 (1.72)</td>
<td>6.22*</td>
</tr>
<tr>
<td>Sentences</td>
<td>Mean F&lt;sub&gt;0&lt;/sub&gt; (Hz)</td>
<td>196.32 (19.97)</td>
<td>194.82 (20.04)</td>
<td>.12</td>
</tr>
<tr>
<td></td>
<td>Mean Intensity (dB)</td>
<td>70.50 (4.84)</td>
<td>71.95 (4.84)</td>
<td>409.99***</td>
</tr>
<tr>
<td></td>
<td>HNR (dB)</td>
<td>12.52 (1.52)</td>
<td>11.43 (2.10)</td>
<td>10.94**</td>
</tr>
</tbody>
</table>

(b) Male participants

<table>
<thead>
<tr>
<th>Type of Voice Sample</th>
<th>Voice parameter</th>
<th>After 24 h Sleep Deprivation, Mean (SD)</th>
<th>After Nocturnal Sleep, Mean (SD)</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustained phonation /a/</td>
<td>Mean F&lt;sub&gt;0&lt;/sub&gt; (Hz)</td>
<td>120.02 (9.97)</td>
<td>117.02 (11.04)</td>
<td>.86</td>
</tr>
<tr>
<td></td>
<td>Mean Intensity (dB)</td>
<td>77.84 (7.05)</td>
<td>77.93 (4.44)</td>
<td>.01</td>
</tr>
<tr>
<td></td>
<td>HNR (dB)</td>
<td>20.98 (3.90)</td>
<td>21.51 (3.32)</td>
<td>.74</td>
</tr>
<tr>
<td></td>
<td>Jitter (%)</td>
<td>.54 (.32)</td>
<td>.58 (.46)</td>
<td>.97</td>
</tr>
<tr>
<td></td>
<td>Simmer (%)</td>
<td>3.14 (3.10)</td>
<td>2.73 (1.08)</td>
<td>.73</td>
</tr>
<tr>
<td>Words</td>
<td>Mean F&lt;sub&gt;0&lt;/sub&gt; (Hz)</td>
<td>135.45 (18.91)</td>
<td>132.28 (21.68)</td>
<td>.35</td>
</tr>
<tr>
<td></td>
<td>Mean Intensity (dB)</td>
<td>73.70 (6.68)</td>
<td>74.06 (4.75)</td>
<td>.16</td>
</tr>
<tr>
<td></td>
<td>HNR (dB)</td>
<td>9.86 (2.19)</td>
<td>9.61 (1.61)</td>
<td>.84</td>
</tr>
<tr>
<td>Sentences</td>
<td>Mean F&lt;sub&gt;0&lt;/sub&gt; (Hz)</td>
<td>122.24 (11.95)</td>
<td>122.04 (15.83)</td>
<td>.01</td>
</tr>
<tr>
<td></td>
<td>Mean Intensity (dB)</td>
<td>73.19 (5.71)</td>
<td>74.51 (5.24)</td>
<td>386.34***</td>
</tr>
<tr>
<td></td>
<td>HNR (dB)</td>
<td>10.54 (1.60)</td>
<td>10.24 (1.73)</td>
<td>.83</td>
</tr>
</tbody>
</table>

* p < .05; ** p < .01; *** p < .001
4. Discussion

Sleep deprivation has negative effects on human functioning, such as cognitive and motor performance, and mood [44]. The effects of sleep deprivation on physiological or biochemical parameters (e.g., cortisol levels, shifts in metabolism) is less clear, with mixed evidence (e.g., [45, 46]. Similarly, the literature is somewhat unclear regarding the effect of sleep deprivation on the human voice. From the perceptual level, voices were rated by listeners as "rouger, less brilliant and more tired" following 24 hours of sleep deprivation [16]. However, the evidence is inconsistent regarding the effect of sleep deprivation on objective - acoustic voice variables. To fill this gap, the current study evaluated the effect of sleep deprivation on objective vocal parameters of young adults. Participants were recorded twice, following nocturnal sleep and following 24 hours of sleep deprivation. The recordings included a sustained phonation, words and sentences production, and were acoustically analyzed for several vocal parameters. The results showed that across all voice samples of females, significantly higher HNR values were found following sleep deprivation than nocturnal sleep (a mean difference of 1.1dB). Let us now discuss this finding, its possible sources and implications.

The HNR is a measure that quantifies the amount of (additive) noise present in the voice signal compared to the harmonic quality. It was found to be a sensitive index of vocal function and vocal quality [47] and is considered a useful measure indicating functional changes in the efficiency of optimal vocal fold vibration [43]. As HNR values are higher (if most of the energy of the signal is in the periodic part, and only a small portion is noise), the voice quality is perceptually better. Lower HNR values are typically found for pathological voices [48, 49]. The current study clearly
shows that voice quality is better (i.e., higher HNR values) after sleep deprivation relative to a night of sleep for female participants. A comparable pattern of results has been documented by Harger [43]. In this study, the average HNR values were higher during the sleep deprived condition (18 hours of sustained wakefulness) compared to the awake condition. This finding indicates that sleep deprivation does not have a detrimental effect on voice. Following a night of sleep deprivation, the voices were functioning in a more optimal fashion, with a greater harmonic component.

Next, we will offer and discuss some possible explanations for this finding (i.e., higher HNR values following a night of sleep deprivation / lower HNR values following nocturnal sleep).

(a) Asynchronous vocal folds' vibration. Attempting to explain the deterioration of voice quality following sleep, Bagnall et al. [16] suggested irregularities in vocal folds' vibration. According to this rationale, since the primary function of the larynx is an airway protector (i.e., preventing aspirations), its "default" posture involves total or partial closure (of both true and ventricular folds). During sleep, the need for such closure (partial adduction) is thought to be greater, as an individual is less alert, more relaxed, and, therefore, less capable of actively protecting the airway. As a result, the larynx is partially closed (indeed, during sleep, inhalation and exhalation typically become more audible, due to glottic narrowing [50]). This closure of the larynx brings the ventricular folds into contact with the superior surface of the true vocal folds, adversely affecting their ability to vibrate in a synchronous manner. Following sleep, vocal folds' vibration remains asynchronous, as an individual is usually relaxed and may be without the necessary focused energy to retract the ventricular folds (which is necessary to ensure clear voice). Such involvement of the ventricular folds leads to an irregular true folds' vibration; hence voice quality is decreased.
(b) Fluid distribution. Alternative explanation for the reduced voice quality following sleep may be related to changes in the distribution of fluids in the mucous membranes of the mouth, nose and throat region which occur during nocturnal sleep. In particular, the vocal folds are covered by a thin layer of liquid, which serves as a physical and biochemical barrier that protects the underlying tissues. This surface liquid layer also maintains optimal biomechanical characteristics of vocal fold mucosa, increases efficiency of vocal fold movement, thus promotes normal voice quality [51]. Presumably, during sleep (i.e., hours with no vocal folds’ use), the throat tissues collect fluids, and mucus builds up on the vocal folds. Hence, the vocal folds slightly swell while sleeping [52]. This (normal) process affects vocal fold vibratory characteristics, resulting in a less periodic vibration, and rougher voice following nocturnal sleep [53].

(c) Dryness of the vocal folds’ mucous due to oral breathing. Oral breathing superficially dehydrates the airway lumen [54]. Thus, individuals who breathe through their mouth during sleep, tend to dry out their vocal folds’ mucous. Such laryngeal dryness, the lack of lubrication and fluid loss are detrimental to phonation [55] and have been postulated to impairs vocal folds’ vibration [53, 56] and to increase the risk for symptoms of vocal effort.

(d) Gastric acid reflux. Acid reflux can also result in a raspier morning voice. During the sleeping hours, stomach acid sometimes makes its way up the esophagus and irritates the vocal folds. This nocturnal reflux of acid containing gastric juices is a very common cause of throat and voice complaints [57]. Patients with laryngopharyngeal reflux commonly complain about voice problems such as minor throat irritations, chronic throat clearing or cough, hoarseness or sore throat, particularly in the morning [58; 59].
It is important to note that the underlying mechanism of the higher HNR values following sleep deprivation remain speculative. For example, in the current study, no information regarding a history of reflux or a pharyngeal pH monitoring have been conducted, nor a monitoring of the breathing pattern. Clearly, these aforementioned alternative explanations warrant further dedicated studies.

Nevertheless, given the normal physiological processes that occur during nocturnal sleep, a deeper (i.e., lower in pitch), raspier and hoarse [59] voice in the morning seems an inevitable result of a night’s sleep [53]. Relatedly, Cho and colleagues [28] posited that "...inflammatory or immune response of larynx can affect voice production and might induce dysphonia in long sleep duration" (p. 9/13). A 24-hours sleep deprivation, on the other hand, prevents these processes from occurring, resulting in a clearer morning voice, with better quality (i.e., higher HNR values for female speakers). Longer sleep deprivation might result in different outcome.

Another issue to consider in interpreting the current findings is the effect of gender. Specifically, why did these differences in HNR between sleep conditions appear only in female, and not in male participants? Differences in voice quality between men and women have been previously reported. For example, Klatt and Klatt [60] have suggested that the female voice is characterized by greater levels of aspiration noise, centered in the high-frequency spectral regions, relative to male voice. This aspiration noise in high frequencies makes the female voice present a more "breathy" quality than the male voice 61,62]. Interestingly, the HNR has been found to be a useful parameter for predicting vocal quality [63].

Attempting to explain the female-specific HNR differences between sleep conditions, one may consider some gender-related differences in the anatomical and
physical traits of the vocal folds [64]. Namely, female vocal folds are about 20–30% thinner than male vocal folds (mainly, the thyroarytenoid muscle is thinner; [65]). The amount and density of collagen in female vocal folds is reduced relative to male vocal folds [66] and the amount of elastin is smaller [64]. In addition, the distribution of hyaluronic acid (HA) within the normal human vocal fold appears to vary based on gender [67]. Specifically, males show a relatively constant distribution pattern throughout the depth of lamina propria, while females show relatively less HA in the superficial than in the deeper areas. Butler and his colleagues [67] suggested that reduced amounts of HA in the superficial layer may predispose females to increased vocal fold injury and increased scarring and implies less protection from vibratory trauma and overuse (see also: [68]). This may explain why female have been found to experience vocal health problems and phono-trauma more frequently than male patients, regardless of their occupation [69].

These gender-related anatomical differences in the laryngeal mechanism may imply that female are more susceptible to the aforementioned physiological processes that occur during a night’s sleep (i.e., changes in the fluid distribution in the throat mucous membranes, dryness of the vocal folds’ mucous due to mouth breathing, or laryngopharyngeal reflux). Possibly, as female vocal folds are more sensitive, the effects of those normal physiological processes on voice quality following nocturnal sleep is more pronounced relative to males (but see: [16], for a non-significant difference between listeners’ ratings of non-fatigued and fatigued voices in females).

A secondary finding of the current study was a slightly reduced mean intensity level following sleep deprivation. This was found for both female and male participants, but only in the sentences production task. This finding is in line with previous studies, suggesting softer and more tired-like voice following sleep
deprivation [16, 20]. However, in the present study, the differences between the sleep and sleep-deprivation conditions in this measure were small (a mean difference of about 1.4 dB) relative to a perceptibly audible threshold (typically, listeners are able to detect changes of sound pressure level when the minimal change of speech stimulus is > 4 dB, [70]). Moreover, these changes in vocal loudness were non-consistent (found only in one of the three voice samples). Therefore, we should be cautious with drawing conclusions from this finding and suggest further studies should look into it as well.

Appropriate sleep duration is important in terms of both general health and quality of life [28]. Yet, sleep deprivation is increasingly common in the modern society, due to various reasons, e.g., lifestyle choice, work or family demands, increase in television viewing and internet use, and physical or psychological problems [71, 72]. Evaluating the effect of sleep deprivation and fatigue on the human voice is clinically important, as effective verbal communication heavily relies on voice [21].

The current study aimed to contribute to the existing literature by investigating the effects of sleep status on changes to objective vocal parameters. We hypothesized there would be changes in the acoustic measurements of participants’ voices as they become sleep deprived, suggesting that the effect of sustained wakefulness on voice was detrimental. Surprisingly, it was after nocturnal sleep that there was a drop in HNR values, indicating lower voice quality. Previous studies attributed vocal changes to reaction to a workload (or task-induced) stress [73], to vocal loading [74] or to fatigue [21]. The current results extend these findings and show that female voice quality (i.e., HNR values) associates with sleep status, as lower HNR characterizes a typical “morning voice”, following a nocturnal sleep. Possibly, such voice changes
may be especially perceived during "sleep inertia" (i.e., the period of time immediately after awakening form sleep; [16]), which was found to impair performance for up to 30 minutes after waking [75].

These findings are in line with previous reports regarding a circadian pattern for the vocal parameters mean F₀ and F₀ range [13]. Such diurnal organization of vocal parameters may have practical clinical consequences. For example, results of voice tests in clinical practice should be controlled for the time of assessment and sleep status. Interestingly, short sleep duration (of ≤5 hours) as well as long sleep duration (≥ 9 hours) have been found to associate with dysphonia [28]. Future studies may assess the effect of sleep duration on specific vocal parameters. Another direction for future research may be the utility of auditory-perceptual ratings from listeners blinded to the sleep status of subjects to determine whether sleep (or sleep deprivation) may produce recognizable, consistent, and measurable voice changes. As noted by Oates [76], "Auditory-perceptual evaluation is the most commonly used clinical voice assessment method, and is often considered a gold standard for documentation of voice disorders." (p. 49). Indeed, some studies have addressed this issue [e.g., 16, 43], yet the findings were inconsistent. Finally, further studies may consider the use of the Cepstral Peak Prominence (CPP) as an acoustic measure of voice quality. The CPP is a measure of the amount of energy in the dominant voice harmonic, and it provides a better visual picture of the degree of harmonic organization. As a speaker's voice changes in quality, this measure changes as the noise component of the voice increases. This measurement has been described as promising in terms of measuring dysphonia and its severity [77], and it has been shown to correspond well to listener auditory-perceptual ratings of voice aberrance (e.g., breathiness; [78]).
Declarations of interest

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Vitae

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