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Perceptual snoring as a basis for a psychoacoustical modeling and clinical patient profiling

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Abstract

Purpose The perceptual burden and social nuisance for mainly the co-sleeper can affect the relationship between snorer and bedpartner. Mandibular advancement devices (MAD) are commonly recommended to treat sleep-related breathing such as snoring or sleep apnea. There is no consensus about the definition of snoring particularly with MAD, which is essential for assessing the effectiveness of treatment. We aimed to stablish a notion of perceptual snoring with MAD in place.

Methods Sound samples, each 30 min long, were recorded during in-home, overnight, automatic mandibular repositioning titration studies in a population of 29 patients with obstructive sleep apnea syndrome (OSAS) from a clinical trial carried out to validate the MATRx plus. Three unspecialized and calibrated raters identified sound events and classified them as noise, snore, or breathing as well as providing scores for classification certainty and annoyance. Data were analyzed with respect to expiration–inspiration, duration, annoyance, and classification certainty.

Results A Fleiss' kappa (>0.80) and correlation duration of events (>0.90) between raters were observed. Prevalence of all breath sounds: snore 55.6% ($N = 6398$), breathing sounds 31.7% ($N = 3652$), and noise 9.3% ($N = 1072$). Inspiration occurs in 88.3% of events, 96.8% contained at least on expiration phase. Snore and breath events had similar duration, respectively 2.58s (sd 1.43) and 2.41s (sd 1.22). Annoyance is lowest for breathing events (8.00 sd 0.98) and highest for snore events (4.90 sd 1.92) on a VAS from zero to ten.

Conclusion Perceptual sound events can be a basis for analysis in a psychosocial context. Perceived snoring occurs during both expiration as well as inspiration. Substantial amount of snoring remains despite repositioning of the mandible aimed at the reduction of AHI-ODI.

Keywords Snoring · OSA; OSAS · MAD

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Introduction

Whether or not snoring is benign, or co-occurring with OSA, snoring can be a hindrance to social interaction and compromise the health of a bedpartner or even prevent couples from sleeping together [1]. Snoring of one or both bedpartners can be seen as a condition with negative consequences and is often the target of interventions meant to mitigate the burden snoring places on the snorer and the partner. Snoring can be thought of as a separate condition caused by turbulence during inspiration and expiration in the upper airway [2], which may be linked to, but does not require obstruction of airflow. Because snoring has an effect on the partner, as well as the snorer, the perception of snore sounds is just as important as how a snore is produced, or the physical nature of the snore sound is. Only after the mental transformation from a sound event into a

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hearing event has been accomplished, can a sound be judged as a snore or normal breathing. This evaluation of noise and sounds depends on the physical characteristics of the sound event, on the psycho-acoustical features of the human ear, as well as on the psychological aspects of the listeners [3]. The psycho-acoustical aspects of (a) sound(s) are defined as the part of the psychophysical aspects involved in the study of sound perception and audiology, namely how humans perceive sounds. In this study we use the terminology of perceptual sound for the perceived sounds by raters while listening to the recordings. More specifically, psychoacoustics is the branch of recognition science studying the psychological responses associated with sound (including noise, speech, and music). This discipline is an interdisciplinary field of many areas, including psychology, acoustics, electric engineering, physics, biology, physiology, and computer science [4]. In order to clinically profile patients (profiling related to the observation and treatment of actual patients), the observation and treatment of patient and bedpartner must be directed toward the natural environment. This is in contrast with theoretical and sleep laboratory studies. To bring the observations in line with the focus and perception of the bedpartner, it is rather up to the bedpartner than a specialist to determine the beginning and ending of sound events. An agreement over nonspecialized observers with respect to the beginning and endings of sound events would provide a basis for the notion of a "perceptual sound event." Attempts have been made in literature to classify and characterize breathing sounds such as snoring through acoustical [5] and psycho-acoustical features such as annoyance [6, 7]. If snoring while sleeping at home is the condition, acoustical and psychoacoustic measures of snoring events in the natural home environment will be most appropriate if ambient acoustical influences can be controlled [8].

Snoring is closely related to obstructive sleep apnea syndrome (OSAS), classified as a sleep-disordered breathing (SDB) by the AASM (AASM-ICSD-3, 2014). The severity of OSAS is most often expressed by the apnea and hypopnea index (AHI) and the oxygen desaturation index (ODI) [9–14]. Two AHI thresholds, 15 and 5, have been used regularly to classify OSAS in severity classes: severe OSAS AHI $\geq$ 15, and (moderate) OSAS AHI < 15 and AHI$\geq$ 5 [15–18]. The criterion AHI < 5 is most often used in operational definitions for primary, simple, and benign snoring [19].

The use of a measure for airflow dysfunction in a definition of a snoring stresses the relation between snoring and obstructions. Snoring and snore related sounds are a predictor for OSA [20]. Despite a measured AHI < 5, the presence of snoring may be due to physiological traits that predispose snorers to developing OSA in the future, in which case truly benign snoring may not exist [21]. The use of an AHI < 5 in definitions of primary, simple, and benign snoring could rather artificially support the hypothesis that "benign" snoring does not exist, since an AHI < 5 and AHI > 0 might already indicate the presence of an obstruction.

Increasing the patency of the upper airway is the aim of most existing therapies for OSA (e.g. dental devices, CPAP, and upper airway surgery) [22] and has a consequence of lowering the AHI. The effect of mandibular reposition appliance (MRA) on snoring has been understudied. A study by Stouder et al. in 2007 suggests that MRA devices may be effective for both palatal and tongue base snoring [23]. To our knowledge the effect of dynamic mandibular advancement on snoring has not been studied.

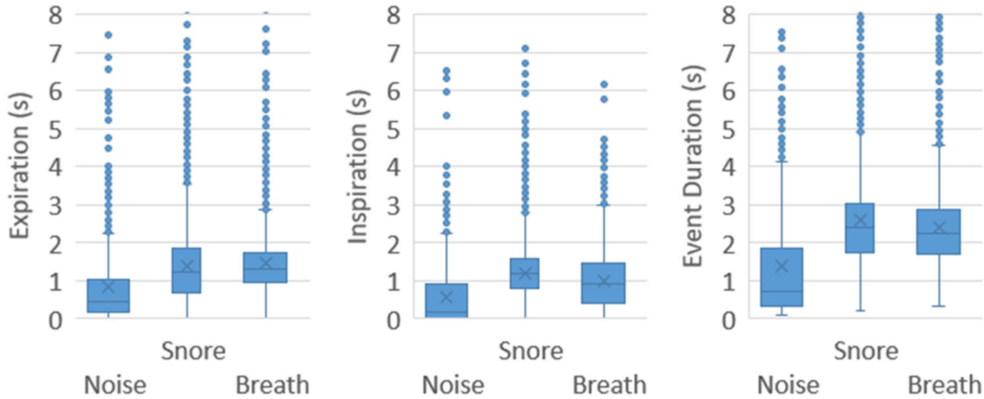
In our study, dynamic mandibular advancement is applied by an automatic control system (MATRx plus) on snoring for OSAS patients. The system is oriented toward lowering of the ODI through a feedback-loop. When snoring is studied in the context of OSAS, most often the inspiration phase is considered a basis for analysis, with begin and end of snore events indicated by a sound expert or an OSAS expert [24, 25]. This restrictive view of what constitutes snoring might be suboptimal when considering snoring as the central condition in a dysfunctional relational context. In what follows, the identification of the snore and other breathing-related sounds of OSA patients in their natural setting is explored by unspecialized raters to mimic real life conditions. The existence of a notion of "a perceived sound event" is investigated and explored to provide a basis and preparation for clinical profiling on patient level based on perceived sound events.

Material and methods

The sample consists of a random selection of 33 patients from 53 patients who participated in a clinical trial designed to validate the efficacy of the MATRx in-home feedback-controlled mandibular positioner (FCMP) [26]. An add-on microphone (Panasonic omnidirectional electret condenser microphone, WM-61A, with the signal conditioned and digitalized at 22050Hz) mounted on the mandibular positioner. The mandibular positioner is attached to maxilla by a set of temporary trays. This ensures fixed position a couple of centimeters from the nose and fixed direction toward the nose. Plus, due to proximity of the microphone to the source of snore sound, the effect of ambient noises or surface reverberations further away from the nose would be minimal. The microphone recommended range of frequency is 20-16,000 Hz with almost a flat response curve. The output of the microphone is conditioned and digitized at 22,000 Hz and 12-bit resolution. The conditioning included amplification of the signal to saturate at 89 db.

A 30-min episode of audio signal from a microphone mounted on the mandibular positioner was chosen at least 1 h after the beginning of sleep. Four audio-recording files could not be used for technical reasons. The analysis data set included three female and twenty-six male patients. The mean age of these patients was 48.7 (sd 11.6) years with a BMI of

Fig. 1 Total duration of all events, events subdivided by type. Duration for inspiration and expiration fractions of the events by event type. Events type determined by at least two raters in agreement with respect to the qualification



34.3kg/m^2 and 180.1 (sd 205.2) baseline snore events per hour and baseline ODI of 31.7 (sd 18.0) events per hour.

One female and two male dental internship students (24 years to 25 years) with normal hearing were asked to determine the beginning and endings of sounds events occurring during the 30-min sound recordings. The raters where nonspecialized to model the bedpartner and to explore whether a notion of "perceived sound events" can be introduced. This notion is then to be a basis for a clinical patient profiling that is more natural and therefore more clinically relevant in the framework of studying the possible negative influence on the bedpartner. Thereafter, the raters were asked to classify the sound effects in the following categories: snore (S), breath (B), and a category called noise (N) for non-breathing-related noises picked up by the microphone. Additionally, they were asked to score certainty of classification and annoyance levels through VAS scales in accordance with Rohrmeier et al. in 2014 [23]. The certainty VAS scale was presented with a color and number coding from zero, uncertain (red) up to ten, totally certain (green). The annoyance VAS ranged from zero, extremely annoying (red) up to ten, not annoying (blue) [6]. None of the raters reported previous experience with a snoring partner. The raters sat in separate identical quiet rooms. An event starts when at least one rater started the event and stops when the all raters ended the event.

The software Audacity for Windows (*Audacity*® 2.3.1 2019) was used on identical laptops (Dell, Precision Mobile 5530, Xeon E-2176M 6 Core 45W 15.6-inch Ultra HD Touch IGZO4 3840x2160) in combination with identical headphones (BOSE Quiet Comfort 25). Sound pressure level calibration was performed to provide identical sound pressure for all raters. A subdivision of the sound events identified by the raters into sound segments was performed based on expiration and inspiration.

The determination of the sound events and their classification was investigated and analyzed with respect to expiration–inspiration and duration. IBM SPSS Statistics 26.0.0.0 64-bit (IBM Corp.) was used for statistical analysis.

Results

A total of 11508 sound events were identified by at least one rater. Out of these events 91.6% (10544) were indicated by all raters, 5.2% (595) by two raters, and 3.2% (369) by one rater only. The duration of events ranged, depending on the rater, from 1.94s (sd 1.36s) up to 2.13s (sd 1.36s). When considering only the matched events the duration was quite similar ranging from 1.96s (sd 1.36s) up to 2.14s (sd 1.37s). The median total durations are quite similar for all raters and indiscriminate from matching of events ranging from 1.80 to 1.96s. The two by two correlation between raters with respect to duration is strong ranging from r=0.90 up to r=0.91. The mean absolute differences in start and end times of the events detected by all raters vary from 0.22 to 0.27s with standard

Table 1 The absence and presence of inspiration and expiration

	Noise		Snore		Breath		Total		Chi^2	Df	p
Inspiration											
Present	639	59.6%	5783	90.4%	3395	93.0%	9817	88.3%	955.7	2	0.00000
Not present	433	40.4%	615	9.6%	257	7.0%	1305	11.7%			
Expiration											
Present	938	87.5%	6188	96.7%	3636	99.6%	10762	96.8%	385.1	2	0.00000
Not present	134	12.5%	210	3.3%	16	0.4%	360	3.2%			

Table 2 Inspiration and expiration

Duration	Mean (s)	SE (s)	sd (s)	Median (s)			
Total	2.41	0.01	1.45	2.2			
By type					K-W	df	*p*
Noise	1.38	0.05	1.8	0.7	1084.4	2	0
Snore	2.58	0.02	1.43	2.4			
Breath	2.41	0.02	1.22	2.2			
Inspiration fraction					K-W	df	*p*
Noise	0.56	0.03	0.86	0.2	890.2	2	0
Snore	1.19	0.01	0.78	1.2			
Breath	0.97	0.01	0.71	0.9			
Expiration fraction					K-W	df	*p*
Noise	0.83	0.03	1.13	0.5	705.8	2	0
Snore	1.39	0.01	1.11	1.2			
Breath	1.44	0.01	0.85	1.3			

deviations from 0.26s to 0.42s. Distributions are quite skewed with outliers (see Fig. 1).

When considering only the events indicated by all raters, a Fleiss' kappa of 0.84 was observed (CI 95% [0.838; 0.851]) for the classification in noise, snore, and breath. Moreover, the absolute classification certainty (certainty score 10) ranged from 64.3% up to 69.9% for snore events depending on the rater with an average of 8.75 (sd 1.38). For breathing sounds, the absolute certainty ranged from 24.3% up to 29.0% with an average of 8.47 (sd 1.49) (see Table 3).

Further analysis will be based on qualification agreement of at least two raters; e.g. if at least two raters indicated that an event is snoring, the event is considered to be a snoring event. All events that are not indicated as noise, snoring, or breathing through this process have been attributed the class "unmatched."

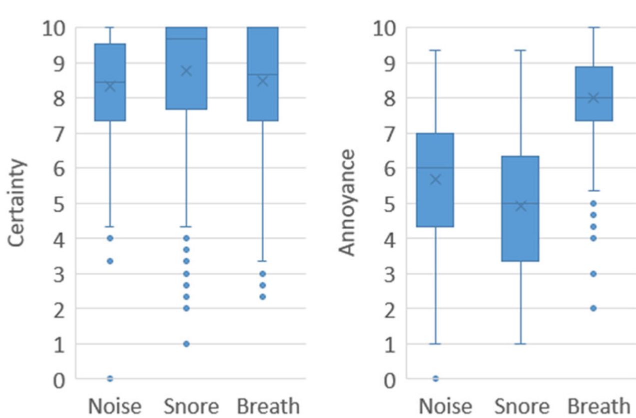


Fig. 2 Average over all raters of annoyance and certainty of classification for different event types for events indicated by at least two raters with agreement on their qualification for at least two raters. A higher certainty score indicates greater classification certainty. A higher annoyance score indicates a sound was less annoying

Snore has the highest prevalence 55.6% (N = 6398), followed by breathing sounds 3652 (31.7%), noise 1072 (9.3%), and the rest category unmatched 386 (3.4%). Inspiration occurs in 88.3% of all events, while 96.8% of the events contained at least one expiration phase. The occurrence of inspiration, respectively expiration depends on the event type. Where for noise the absence of inspiration is relatively high (40.4%), this is not true for snore (9.6%) and breathing events (7.0%), expiration is present in almost every breathing sound event (99.6%), and also for the snore events the presence of expiration is extremely high (96.7%), for noise events expiration is present in nearly nine out of ten events (87.5%) (see Table 1).

Snore and breath events have similar duration, respectively 2.58s (sd 1.43) and 2.41s (sd 1.22). The time fraction of inspiration during a snore event is 0.20 shorter than the expiration fraction. For breathing this difference is more elevated: 0.47s. Noise is always substantially smaller in duration than the other event types (Fig. 2, Table 2).

The annoyance is lowest for breathing events (the higher the score, the lower the annoyance 8.00 sd 0.98) and highest for snore events (4.90 sd 1.92) (see Table 3).

Table 3 The annoyance and absolute certainty

		Mean	SE	sd	Median	K-W	df	*p*
Annoyance	Noise	5.66	0.05	1.61	6	5200.3	2	0.00000
	Snore	4.90	0.02	1.92	5			
	Breath	8.00	0.02	0.98	8			
Certainty	Noise	8.33	0.05	1.38	8.4	242	2	0.00000
	Snore	8.75	0.02	1.64	9.7			
	Breath	8.47	0.03	1.49	8.7			

Discussion

In this present study with unspecialized raters, the three raters were free to indicate the beginning and ending of the sound events by a hearing test. It is imperative that there would be a relatively high agreement between the events indicated to be able to talk about a "perceptual snoring event." The high observed agreement between raters means that such a paradigm is an appropriate basis for breathing-related sound research, psycho-acoustical modeling, and clinical patient profiling. Note that when considering partner and bedpartner it is not especially required to have a reliable snoring score, since the uniqueness of the couple prevails in snoring as aspect of the dyadic relation for therapeutic interventions. We found that the classification into sound types is reliable despite the freedom of raters in indicating of beginning and ending of sounds. A high Fleiss' kappa (>0.80) and strong correlations between duration of events were observed (r>0.90) between raters with an extremely high certainty of scoring. Note that our raters were all very similar: having no previous experience with snoring partners, normal hearing, and between 24 and 25 years of age.

Dafna in 2013 restricted the snoring events to breathing sounds during inspiration in preparation of an automatic detection in an OSAS population without protrusion. They found detected events to have a duration with a rather symmetric distribution, a central value of 1.5s, ranging between 0.2 and 3.0s [27]. This in contrast with our findings with respect to perceived snoring, the perceived snoring events were considerably longer (2.58s sd 1.43s), with a distribution showing outlies (Fig. 1, Table 2), containing inspiration (1.19s sd 0.78s) as well as expiration (1.39s sd 1.11s) (see Table 2). Similar to Dafna et al. 2013, Levartorvsky et al. 2016 indicate that most studies defined snoring based on sound intensity exceeding a certain amplitude, some requiring an oscillating component or selected snores, and decide to use intensity as a basis for snoring, respectively >20dB and >50dB in their snoring definition [27, 25]. When doing so they observed an extremely high percentage of inspiration, respectively 97.5% and 97.0% in contrast to the nearly equivalent contribution of inspiration and expiration to the perceived snoring events in our study. In our study, inspiration occurs in 90.4% of all perceived snore events and expiration in 96.7% (see Table 1). It seems unlikely that the extreme difference would be completely explained by the activation in our study although the prolapse of the soft palate during activation might contribute to oscillating sounds during expiration in patients with OSAS [28]. Assuming that the breathing and snoring sounds are mainly generated in nose valve and velo-oro-pharynx respectively, the microphone is much closer to the source of breathing sound. That can explain the fact that the raters scored so many breathing events. The participants were OSA patients and the audio files were collected when their mandible was protruded. Also, the genioglossus [29] and the epiglottis [30, 31] might be influenced by the protrusion and cause snoring sounds.

Annoyance is of extreme importance as a psychoacoustic factor when considering bedpartner relations. In the study by Rohrmeier et al. 2014 this aspect was considered together with certainty of classification of 55 sequences of 3 similar successive breath sounds or snoring sounds of 23 patients with a diverse spectrum of apnea [24]. The classifications were performed by a substantial number (25) of diverse raters with respect to experience with snoring and medical profession. The aim of that paper was not annoyance as such, but rather the possibility to use psychoacoustic features for classification, and they only report annoyance through a boxplot without specifications. The results agree with the present findings: snoring was considered more annoying with extreme variability agrees with the high annoyance found in our study and the substantially lower annoyance for breathing sounds with more variability in our study. Dreher et al. 2009 reported a substantial variability in annoyance with respect to the listener [32]. The MRA may treat the OSA patients and leave them with residual snoring with substantial annoyance and prevalence.

Conclusion

Reliability analysis in the present study shows that a "perceptual sound/snoring event" concept can be introduced as a basis for analysis of snoring in a psychosocial context as well as patient profiling. This perceptual snoring event most often contains both inspiration and expiration and therefore differs from the snoring event regularly used as a basis for snoring studies. When a dynamic mandibular advancement system is applied aimed at the reduction of ODI–AHI, substantial snoring remains during both expiration and inspiration. Clinical relevance is the introduction of a notion that can be applied to study snoring from a social interactive point of view. Our findings might change the approach for treatment of the nuisance's aspect of snoring. Further research is needed to confirm and to explore how perceptual sound/snoring events can be used in clinical patient profiling to mitigate negative effects for bedpartners and to validate the notion of "perceptual sound event" with the bedpartner.

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Declarations

Ethics approval and consent to participate The clinical trial was approved by the Conjoint Health Research Ethics Board of the University of Calgary, and informed consent was obtained from all participants. (Ethics ID: E-24903)

Conflict of interest The co-authors Seyed Abdolali Zareian Jahromi, Dillon A Hambrook, and John E. Remmers are employees affiliated with the Zephyr Sleep Technologies, Calgary, Canada.

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