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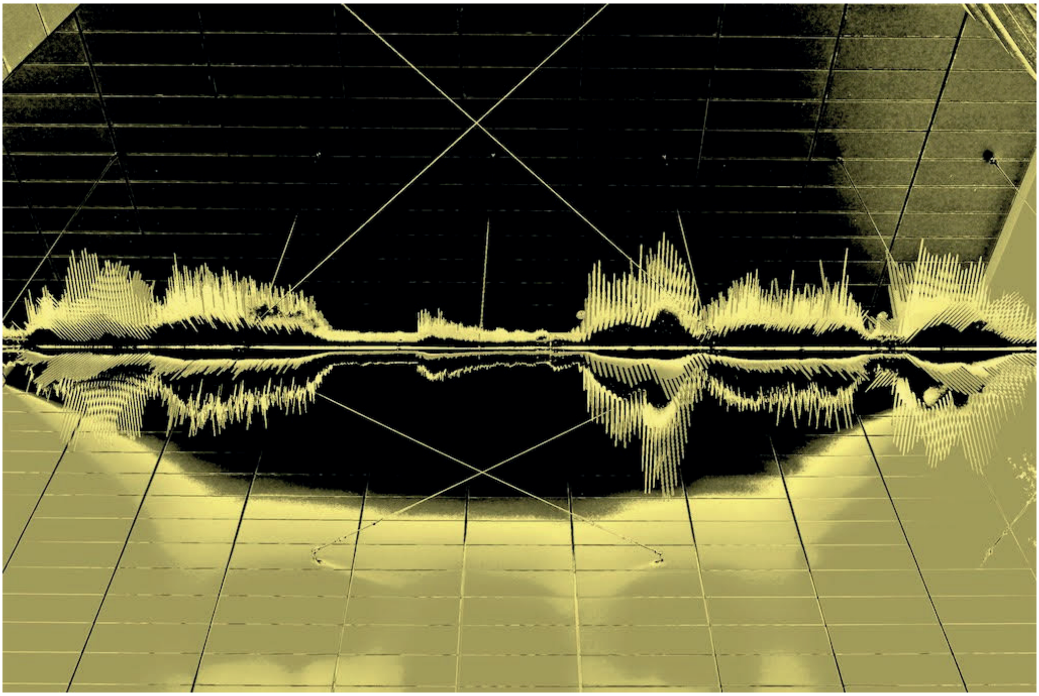
The female voice in vocally demanding professions

– Field studies using portable voice accumulators



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THE FEMALE VOICE IN VOCALLY DEMANDING PROFESSIONS: FIELD STUDIES USING PORTABLE VOICE ACCUMULATORS

Annika Szabo Portela

Stockholm 2017

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Division of Speech and Language Pathology

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Stockholm 2017

To my father for the endless source of knowledge and inspiration. Without your unconditional love and support, this dissertation would not have seen the light of day.

Cover: Ebba Matz’ sculpture “SHH, QUIET, LISTEN”
Photo by Christian Portela with permission from Ebba Matz

ABSTRACT

Objectives: Methods to register voice use outside the voice clinic, at work, are important for assessment of work-related voice disorders. Such methods must be reliable and valid and at the same time practical and easy to handle. The overall aim of this thesis was to evaluate portable devices for long-term voice registrations and to assess voice use at work in women with vocally-demanding professions.

Materials and methods: In **Study I** a voice accumulator, with two different software, was evaluated regarding speaking fundamental frequency and phonation time, with reference to simultaneous studio recordings. The voice accumulator was also tested in field condition. Participants were two vocally healthy women and two vocally healthy men in both the studio and the field conditions. In **Study II**, the same device was tested in studio condition where one female participant simulated different voice qualities. In addition, the device was compared to simultaneous DAT recordings in field condition. Participants were three vocally healthy female preschool teachers. In **Study III**, the same type of voice accumulator was used to collect voice data from 12 vocally healthy female preschool teachers during two days to compare data between work and leisure. In **Studies IV and V** a more advanced device was used that could measure the sound pressure levels of the speaker's voice and the environmental noise, in addition to fundamental frequency and phonation ratio. Forty women, 20 with work-related voice disorders and 20 vocally healthy controls, matched for workplace and profession, were monitored during seven days. Data comprised approximately 95 hours for each participant, categorized into work and leisure based on information from diaries. Data was analyzed with environmental noise as the experimental factor, using the device's software program and MATLAB. The participants also rated estimated speaking time, voice symptoms and perceived disturbing noise four times a day during the week using Visual Analogue Scales. A total of 4,480 data points were collected, the response rate was 96%.

Results: Study I stressed the importance of careful placement and firm attachment of the contact microphone to the speaker's neck for reliable detection of vocal fold vibrations. If so, the agreement between the voice accumulator's two software and the reference studio recording was good. Field recordings indicated an activity dependent phonation time. **Study II** found that the voice accumulator measured fundamental frequency and phonation time reliably for different voice qualities, except for creaky voice. It also failed to register phonation at frequencies above 440 Hz as well as phonation at low sound pressure levels. **Study III** showed that preschool teachers used higher average fundamental frequency and phonation time during work as compared to leisure time, indicating high vocal load caused by the activities at work. Results from **Study IV** confirmed the finding in Study III that phonation ratio was higher during work than during leisure. When comparing results between patients and controls no significant differences were found for fundamental frequency, phonation ratio or voice level. However, significant differences were found between the patient groups; the patients with vocal nodules and their controls were exposed to significantly higher levels of environmental noise, they spoke more and louder, and used higher fundamental frequency than the patients

with phonasthenia and their controls, in the work condition. **Study V** showed that the patients rated vocal fatigue and hoarseness as significantly higher than did the controls, as expected. The average ratings increased during the workday and remained high in the evening. A majority of the participants (32 of 40) showed significant correlations between self-rated speaking time and phonation ratio. The patients with vocal nodules and their controls rated the levels of disturbing noise as significantly higher compared to the patients with phonasthenia and their controls during workdays, which was in agreement with the instrumental measurements of the environmental noise levels.

Conclusions: The portable devices used in the present thesis were found to be useful for long-time measurements of voice use, although all had their limitations. There were no significant differences in voice use between patients and their matched controls at work, suggesting that the occupational demands and the work environment have a greater impact on vocal behaviour than individual factors. The average environmental noise reached levels that were clearly detrimental to speech communication. Therefore, a reduction of environmental noise levels seems crucial for improving the ergonomic conditions in communication-intensive and vocally-demanding workplaces. Since subjective ratings and instrumental measures had similar patterns during the week, it seems that patients and vocally healthy controls have a quite accurate perception of how much they talk and of the disturbing environmental noise. Thus, self-ratings are useful to collect, if this is done in a structured way. The difficulties encountered in long-term accumulation of data from dysphonic voices, for example at extraction and averaging of fundamental frequency of irregular vocal fold vibrations, have to be acknowledged, as does the balance between the methods' accuracy of measurements and the need to be user-friendly.

SAMMANFATTNING

Syfte: Metoder för att registrera röstanvändning utanför röstkliniken under arbete är viktiga vid bedömning av arbetsrelaterade röststörningar. Sådana metoder måste vara valida och reliabla och samtidigt praktiska och lätta att använda. Det övergripande syftet med denna avhandling var att utvärdera bärbar utrustning för långtidsmätningar av rösten samt att undersöka röstanvändning under arbete hos kvinnor med röstkrävande yrken.

Material och metoder: I **Studie I** utvärderades en röstackumulator och dess två olika mätprogram avseende grundtonsfrekvens och fonationstid i jämförelse med samtidiga studioinspelningar. Röstackumulatorn testades också i fält. Deltagare var två röstfriska kvinnor och två röstfriska män i både studio- och fältstudien. I **Studie II** testades samma utrustning i studio med en kvinnlig deltagare som simulerade olika röstkvaliteter. Utrustningen jämfördes också med samtidiga DAT-inspelningar i fält. Deltagare var tre röstfriska kvinnliga förskollärare. I **Studie III** användes samma typ av röstackumulator för att samla in röstdata från 12 röstfriska kvinnliga förskollärare under två dagar för att jämföra data mellan arbete och fritid. I **Studierna IV och V** användes en mer avancerad utrustning som också kunde mäta ljudtrycksnivån på talarens röst och på omgivningsbullret, utöver grundtonsfrekvens och fonationskvot. Fyrtio kvinnor, 20 med arbetsrelaterade röststörningar och 20 röstfriska kontroller , matchade för arbetsplats och yrke deltog under sju dagar. Data omfattade cirka 95 timmar för varje deltagare, uppdelat i arbete och fritid baserat på information från dagliga anteckningar. Data analyserades med omgivningsbullret som experimentell faktor, med hjälp av ackumulatorns mjukvara och med MATLAB. Deltagarna skattade också talad tid, grad av röstsymptom och störande buller fyra gånger om dagen under veckan på visuella analogskalor, vilket gav totalt 4,480 datapunkter, motsvarande 96% svarsfrekvens.

Resultat: Studie I visade på vikten av noggrann placering av kontaktmikrofonen mot huden på talarens hals för tillförlitlig detektion av stämbandsvibrationerna. Om så gjordes, var överensstämmelsen mellan röstackumulatorns två mätprogram och referensstudio-inspelningarna god. Fältinspelningarna tydde på en aktivitetsberoende fonationstid. I **Studie II** framkom att röstackumulatorn mätte grundtonsfrekvens och fonationstid på ett tillförlitligt sätt för olika röstkvaliteter, med undantag för knarr. Den misslyckades också med att registrera fonation vid frekvenser över 440 Hz samt vid låga ljudtrycksnivåer. **Studie III** visade att förskollärare använde högre grundtonsfrekvens och fonationskvot under arbetstid jämfört med fritid, vilket indikerade hög röstbelastning orsakad av aktiviteterna i arbetet. Resultat från **Studie IV** bekräftade resultatet i studie III att fonationskvoten var högre under arbetstid än fritid. Vid jämförelse av resultaten mellan patienter och kontroller framkom inga signifikanta skillnader avseende grundtonsfrekvens, fonationskvot eller röststyrka: Däremot framkom signifikanta skillnader mellan patientgrupperna; patienter med stämbandsknottror och deras kontroller utsattes för signifikant högre nivåer på omgivningsbullret, de talade mer och starkare, och använde högre grundtonsfrekvens under arbete än patienter med fonasteni och deras kontroller. **Studie V** visade att patienterna skattade rösttrötthet och heshet i signifikant högre grad än kontrollerna, som förväntat. Skattningen av dessa symptom ökade under

arbetsdagen och förblev höga under kvällen. En majoritet av deltagarna (32 av 40) visade signifikanta korrelationer mellan uppskattad taltid och fonationskvot. Patienterna med stämbandsknottror och deras kontroller skattade signifikant högre nivåer av störande buller jämfört med patienter med fonasteni och deras kontroller under arbetsdagar, vilket överensstämde med de instrumentella mätningarna av nivån på omgivningsbullret.

Slutsatser: De bärbara utrustningarna som användes i denna avhandling visade sig vara användbara för långtidsmätningar av röstanvändning, även om de alla hade sina begränsningar. Det fanns inga signifikanta skillnader i röstanvändning hos patienter jämfört med deras matchade kontroller under arbete, vilket tyder på att arbetets röstkrav har större inverkan på röstbeteendet än faktorer relaterade till individerna. Det genomsnittliga omgivningsbullret nådde nivåer som klart stör talkommunikation. Därför är försök att minska ljudnivån viktiga för att förbättra röstergonomiska förhållanden på kommunikationsintensiva och röstkrävande arbetsplatser. Eftersom subjektiva skattningar och instrumentella mätningar visade liknande variation under veckan förefaller det som att patienter och röstfriska kontroller har relativt god uppfattning om hur mycket de pratar och om störande omgivningsbuller. Således kan självskattningar vara meningsfulla att använda om insamling görs på ett strukturerat sätt. Svårigheterna som uppkommer vid långtidsackumulering av data från dysfoniska röster, till exempel vid extraktion och medelvärdesbildning av grundtonsfrekvens vid oregelbundna stämbandssvängningar, måste uppmärksammas, liksom balansen mellan metodernas mätnoggrannhet och användarvänlighet.

LIST OF SCIENTIFIC PAPERS

The first three papers were included in the respondent's Licentiate Thesis "The Voice at Work: Evaluation of Methods for Voice Documentation with Focus on Daycare Centres" from 2004. Paper IV and V are the result of the second half of the Ph.D. programme.

I. **Szabo A,** Hammarberg B, Håkansson A, Södersten M. A voice accumulator device: evaluation based on studio and field recordings. Logoped Phoniatr Vocol. 2001;26(3):102-17.

II. **Szabo A,** Hammarberg B, Granqvist S, Södersten M. Methods to study preschool teachers' voice at work: simultaneous recordings with a voice accumulator and a DAT recorder. Logoped Phoniatr Vocol. 2003;28(1):29-39.

III. **Szabo Portela A,** Hammarberg B, Södersten M. Speaking fundamental frequency and phonation time during work and leisure time in vocally healthy preschool teachers measured with a voice accumulator. Folia Phoniatr Logop. 2013;65(2):84-90.

IV. **Szabo Portela A,** Granqvist S, Ternström S, Södersten M. Vocal behavior in environmental noise: comparisons between work and leisure conditions in women with work-related voice disorders and matched controls. J Voice. 2017.

V. **Szabo Portela A,** Södersten M. Subjective and instrumental voice and noise data from week-long registrations in women with work-related voice disorders and matched controls. Manuscript.

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LIST OF ABBREVIATIONS

C nodules	Controls to patients with vocal nodules
C phonasthenia	Controls to patients with phonasthenia
DAT	Digital audio tape
dB	Decibel
ENT	Ear, nose and throat
f_o	Fundamental frequency
HP filter	High-pass filter
Hz	Hertz
L_{eqN}	Equivalent continuous level of the environmental noise
L_{eqV}	Equivalent continuous level of the voice
LP filter	Low-pass filter
MATLAB	Matrix laboratory software
P phonasthenia	Patients with phonasthenia
Phonation time	The time during which the vocal folds are vibrating
Phonation ratio	The phonation time divided by the total recorded time
P nodules	Patients with vocal nodules
SD	Standard deviation
SLP	Speech and language pathology
SOR	Self-to-other ratio
SPL	Sound pressure level
ST	Semitones
Swe-VAPP	Swedish translation of the Voice Activity and Participation Profile
VAC	Voice accumulator
VACF0	The voice accumulator's software optimized for f_o
VACLF1	Voice accumulator LF1
VACPT	The voice accumulator's software optimized for phonation time
VAS	Visual Analogue Scale
VHI	Voice Handicap Index
VHI-T	Voice Handicap Index Throat

1 INTRODUCTION

Individuals with vocally-demanding occupations are at risk for developing voice disorders because of risk factors in the work environment. Monitoring of voice use at work, outside the voice clinic, is important for understanding the impact of work on the voice. "Considering the complexity of human vocal behaviour and of the physical environment, how does one measure voice use in daily life in a valid, reliable and practical way?" and "Does voice use differ between vocally healthy individuals from those diagnosed with a work-related voice disorder?" These two questions sparked this exploratory thesis project; an endeavour that spans over almost two decades. During these years, the technology for ambulatory voice monitoring has evolved. The understanding of how vocal load and individual and environmental risk factors affect vocal health has also increased considerably. Nevertheless, these questions prevail. The thesis addresses these two questions and more specific enquiries about female voice use in vocally-demanding professions. Different methods were used for long-term measurements of voice use during work and leisure time. Also, subjectively reported voice data and ratings of voice symptoms were collected for comparison with the instrumental data to obtain the perspectives of patients and vocally healthy participants on their voice use. Methodological advances and challenges related to the use of portable voice monitors in field studies, and systematic collection of subjective data, are discussed in light of the results of this thesis and of future needs.

1.1 METHODOLOGY OF LONG-TERM VOICE MONITORING

Compared to voice recordings in laboratory conditions, field recordings have the advantage of capturing vocal behaviours more closely related to the work environment and everyday life (Manfredi & Dejonckere, 2016). However, it is methodologically challenging to measure voice use in real life situations. Laboratory conditions allow for control of confounding factors, and of background noise, which otherwise needs to be separated from the speech signal (Granqvist, 2003; Södersten, Granqvist, Hammarberg, & Szabo, 2002). To simulate a natural sound environment in the laboratory, artificial noise has been presented in headphones, or over loudspeakers, to create a situation where the speaker is encouraged to make him- or herself heard over the noise (Aronsson, Bohman, Ternström, & Södersten, 2007; Bottalico, Graetzer, & Hunter, 2015; Södersten, Ternström, & Bohman, 2005; Whitling, Rydell, & Lyberg Åhlander, 2014). Nevertheless, it is questionable if recordings under laboratory conditions are representative of the speaker's spontaneous voice use in everyday life (Carding, Wilson, MacKenzie, & Deary, 2009). Fundamental frequency (f_o), for instance, has been reported to vary more in spontaneous speech in field conditions compared with text reading under laboratory conditions (Rantala, Lindholm, & Vilkman, 1998). Average f_o and voice sound pressure level (SPL) have, furthermore, been found to be higher in field conditions compared with recordings in a quiet room (Lindström, Ohlsson, Sjöholm, & Waye, 2010; Puglisi, Astolfi, Cantor Cutiva, & Carullo, 2017; Rantala, Lindholm, et al., 1998; Södersten et al., 2002). Therefore, the emergence of portable microprocessor-based voice accumulators was an important step forward for the field of occupational voice.

1.1.1 Voice accumulators

The first step out from the laboratory into the field was taken in the 1970s. Holbrook (1977) measured f_o and voice SPL for 12 elementary school teachers, and also tested a portable voice intensity controller on 32 patients with vocal nodules and hyperfunction (Holbrook, Rolnick, & Bailey, 1974). In Japan, two studies followed in which phonation time was measured for vocally healthy adults with different occupations, as well as for children, and a patient with spasmodic dysphonia (Ryu, Komiyama, Kannae, & Watanabe, 1983; Watanabe, Shin, Oda, Fukaura, & Komiyama, 1987). *Phonation time* is the time during which the vocal folds are vibrating. *Phonation ratio* has been used in other studies (see Table 1), which is the phonation time divided by the total recorded time. Next, in Sweden, Ohlsson, Brink, and Löfqvist (1989) developed a voice accumulator that was used to measure f_o and phonation time in 10 speech language pathologists and 10 nurses. Masuda, Ikeda, Manako, and Komiyama (1993) included patients with vocal nodules in their study containing 29 office workers, preschool teachers and elementary school teachers. Thereafter, field studies including patients have been sparse until recently, as can be seen in Table 1. Table 1 includes studies with voice accumulators and voice dosimeters in chronological order that have registered f_o, phonation time and/or voice SPL.

More recent devices for ambulatory monitoring of voice use are The Ambulatory Phonation Monitor (APM) (KayPENTAX, Montvale, NJ, USA) (Hillman, Heaton, Masaki, Zeitels, & Cheyne, 2006); the National Centre for Voice and Speech dosimeter (NCVS, Denver, CO, US) (Hunter & Titze, 2010); the VoxLog (Sonvox AB, Umeå, Sweden) (Lindström, Waye, Södersten, McAllister, & Ternström, 2011); The Voice-Care device (PR.O.VOICE S.r.l, Turin, Italy) (Astolfi, Carullo, Pavese, & Puglisi, 2015). While the other voice accumulation and voice dosimetry devices disregard external noise, VoxLog measures both the level of the voice and of the environmental noise (Van Stan, Gustafsson, Schalling, & Hillman, 2014; Wirebrand, 2012). VocaLogVocal Activity Monitor (Griffin Laboratories, Temecula, CA, USA) is an intensity monitor for clinical use that gives biofeedback on vocal loudness (Searl & Dietsch, 2014).

1.1.2 Digital Audio Tape Recorders

Table 2 includes studies with portable DAT (Digital Audio Tape) recorders that have been used to study voice use at work. For example, parts of a working day, such as the first and last lessons for school teachers, have been recorded and analyzed (Jonsdottir, Laukkanen, & Vilkman, 2002; Jonsdottir, Rantala, Laukkanen, & Vilkman, 2001; Rantala, Haataja, Vilkman, & Körkkö, 1994; Rantala, Lindholm, et al., 1998; Rantala, Paavola, Körkkö, & Vilkman, 1998; Rantala & Vilkman, 1999; Rantala, Vilkman, & Bloigu, 2002). Furthermore, customer call centres workers (Ben-David & Icht, 2016; Lehto, Laaksonen, Vilkman, & Alku, 2006, 2008), preschool teachers (Södersten et al., 2002) and singing students (Schloneger & Hunter, 2016) have been recorded with DAT recorders during 1-3 workdays.

Table 1. Studies that have used voice accumulators or voice dosimetry devices in chronological order from 1974 to 2017.

Authors	Year	Participants	Parameters	Measuring time	Device and main results
Holbrook, Rolnick, Bailey	1974	32 patients with vocal fold lesions and hyperfunction	SPL	Treatment time of in average 5.3 weeks	A portable voice intensity controller proved to be effective in a treatment program for the patients.
Holbrook	1977	12 elementary school teachers	Phonation time, SPL	6 hours, 5 workdays	A portable voice accumulator. The teachers' phonation time was 21%. The average percent of loud talking was 27%.
Ryu, Komiyama, Kannae, Watanabe	1983	11 clerks, physicians, nurses, bus guide	Speaking time	12 hours per day, total of 34 days	A speech accumulator. Average speaking time was 110 min per day. A bus guide had the longest phonation time of 182 min for a day. A clerk had the shortest phonation time of 33 min.
Watanabe, Shin, Oda, Fukaura, Komiyama	1987	1 patient with spasmodic dysphonia, 20 vocally healthy adults, 30 children	Speaking time	10-12 hours per day. 58 days for the patient. 6 days for the control groups	A speaking timer. The patient had a speaking time of 8 min 12 sec ± 3 min 30 sec/h, the vocally healthy adults 6 min 25 sec ± 1 min 36 sec/h and children 9 min 30 sec ± 3 min 15 sec/h.
Ohlsson, Brink, Löfqvist	1989	10 speech therapists, 10 nurses	Phonation time, f_o	2 workdays	Voice Accumulator. The speech therapists had a significantly lower f_o and longer phonation time 7% (4.14 min/h) than the nurses 5% (3.18 min/h)
Masuda, Ikeda, Manako, Komiyama	1993	29 office workers, kindergarten teachers, elementary school teachers, patients with vocal nodules	Phonation time, SPL	8 hours per day, total of 131 days	Speech intensity/speech time accumulator. Office workers had a phonation time of 33 min 36 sec (± 13 min 36 sec)/day. Teachers and patients had higher phonation time of 102 min (± 22 min 54 sec)/day, and preschool teachers 95.2 (±17.4 min). For teachers half of the phonation time was with high voice intensity.
Buekers, Bierens, Kingma, Marres	1995	72 teachers, preschool teachers, bookkeepers, sports instructors, tele-phone operators, receptionists, nurses, speech therapists	Speaking time, SPL	3-8 hours, 1 workday	Voice accumulator. Teachers, preschool teachers and sport instructors had the greatest vocal load and bookkeepers had the least. Speech therapists, receptionists and telephone operators spoke predominantly at soft intensities because of individual communication with one person at the time.
Airo, Olkinuora and Sala	2000	11 adult females	Speaking time, SPL	8 hours	Noise exposure analyser. The subject's speaking time was accurately detected in a quiet environment as well as in the presence of background noise in laboratory conditions.

Sala, Airo, Olkinuora, Simberg, Ström, Laine, Pentti, Suonpaa	2002	51 (female preschool teachers, 25 (female nurses)	Speaking time, SPL of speech and background noise, RASTI	6-7 hours, 1 workday	Noise exposure analyser. Teachers' average speaking time was 40 ± 10% (range 19-63%), the nurses' 28 ± 12% (range 6-50%). The teachers' average speech SPL was 78 ± 2.3 dB (range 74-85 dB). The nurses' average speech SPL was 72 ± 2.7 dB (range-76 dB). The average background noise levels at daycare centres were 67 ± 3 dB (L_{Aeq}).
Carroll, Nix, Hunter, Emerich, Titze, Abaza	2006	5 male and 2 female professional singers	Time, cycle dose distance dose, IPSI subjective ratings of effort and discomfort	Two weeks	The NCVS dosimeter. A vocal dosimetry pilot study of vocal fatigue. Trend that IPSV and vocal effort increased with large vocal dose. Spikes in vocal load reflected as "harsher" subjective ratings the same day and 24-72 hours later. At least 48 hours of vocal rest needed to improve subjective evaluations after vocal load.
Titze, Hunter, Svec	2007	57 school teachers	Voice SPL, f_o, phonation time, quality of soft phonation, self-ratings of effort and discomfort	Two weeks, measures taken every 2-hour interval	The NCVS dosimeter was used to investigate voicing and silence periods in daily and weekly vocalizations of teachers. On average, the teachers had 1800 occurrences of voicing/ h at work and 1200 occurrences/h while not at work. Voicing occurred 23% of the total time at work, and 13% during off-work hours, 12% on weekends.
Halpern, Spielman, Hunter, Titze	2009	10 teachers	Daily IPSV ratings, perceptual analysis of the teachers' IPSV	Two weeks, ratings every 2 hours	The NCVS dosimeter. Despite no significant agreement between teachers and clinicians ratings the results supports the potential usefulness of IPSV as a simple tool to detect voice changes
Hunter and Titze	2010	57 teachers	Voicing % per hour, average f_o, and voice SPL	Two weeks 9 am to 3 pm and 4 pm to 10 pm	The NCVS dosimeter. In occupational settings: higher voicing % per hour, 1 dB SPL louder, increased pitch with upward trend than in nonoccupational settings. Some apparent gender differences
Lindström, Waye, Södersten, McAllister, Ternström	2011	13 preschool teachers	f_o , voice and noise SPL	1 day, 2 h in the morning and in the afternoon	Voxlog and DAT-recorder. Observations of the relationship between noise exposure and preschool teacher voice usage at pre-schools. Correlations between f_o vs noise SPL, and noise vs voice SPL varied considerably. Thus, teachers reacted individually to the noise exposure.

Morrow, Connor	2011a	7 music teachers and 5 elementary classroom teachers	Voice SPL, phonation time, vocal load calculated by cycle and distance dose	5 workdays	APM. Statistically significant differences in all measures were found between the two teacher groups suggesting typical vocal loads for music teachers are substantially higher than those for classroom teachers
Morrow, Connor	2011b	7 music teachers	Voice SPL, phonation time, vocal load calculated by cycle and distance dose	5 workdays + 2nd week with an amplifier	APM. Voice amplification reduced voice SPL, cycle dose, distance dose and phonation time, being an effective intervention to decrease the potentially damaging vocal loads
Bottalico, Astolfi	2012	40 primary school teachers (36 females and 4 males)	.Voicing % voice SPL, subjective ratings, RT	73 working days, 2 schools with different room acoustics	Voice Care. Investigations into vocal doses and parameters pertaining to primary school teachers in classrooms with different RT. No sign differences in the instrumental data but in the voice SPL and subjective ratings.
Gaskill, O'Brien, Tinter	2012	2 elementary school teachers (1 with no and 1 with voice complaints)	f_o, distance dose, cycle dose	3 weeks all time at work, last week with an amplifier	APM. Voice amplification reduced all voice parameters, more for the teacher with voice complaints
Mehta, Zanartu, Feng, Cheyne, Hillman	2012	3 vocally healthy males and 3 females with voice disorders	f_o, voice SPL, glottal airflow properties, cycle and distance dose	7 days	Smart phone platform. Method development to differentiate between hyperfunctional and normal vocal behavior patterns.
Cantarella, Iofrida, Boria, Giordano, Binatti, Pignataro, Dejonckere	2014	92 call center operators (25 males and 67 females=	f_o, voice SPL, phonation time, VHI	1 day, Work and extrawork	APM. Average phonation time at work was 14.74% (range 4% to 31%). VHI was not related to number of work hours and phonation time.
Ghassemi, Van Stan, Mehta, Zanartu, Cheyne, Hillman, Guttag	2014	12 patients with vocal nodules and 12 matched controls	f_o, voice SPL phonation time	1 week	Smart phone platform. Able to detect vocal hyperfunction from the ambulatory neck-surface acceleration feature and differenciate between patients and controls.

Lyberg Åhlander, Pelegrin Garcia, Whitling, Rydell, Löfqvist	2014	14 teachers with and 14 without voice complaints	f_o, voice SPL phonation time, room acoustic properties	1 workday	APM. Phonation time and cycle dose higher for females with voice complaints. Differences in f_o related to voice SPL and room acoustics, between the groups
Remacle, Morsomme and Finck	2014	12 kindergarten teachers and 20 elementary school teachers	f_o, voice SPL phonation time, time dose, distance dose, and cycle dose	1 week	APM. Higher cycle dose and distance dose for kindergarten teachers suggesting more vocally loading work than elementary teachers
Astolfi, Carullo, Pavese, Puglisi	2015	6 professors, 22 university students, 25 primary school teachers	Voicing and silence periods, RT	Short laboratory monologues and longer times in classrooms	APM and Voice-Care. Duration of voicing and silence periods of continuous speech in different acoustic environments was measured. Tendency to increase the voicing periods as the RT increased in order for the speaker to be understood
Misono, Banks, Gaillard, Goding, Yueh	2015	11 vocally healthy 11 patients after phonosurgery	Phonation time and sound level. Self ratings of voice use	2 hours for the vocally healthy, and 2 days pre and post surgery for the patients	VocaLog was used for clinical utility in regards to voice rest on 11 patients with laryngeal pathologies pre- and post surgery. A moderate association between self-reported voice use and measured phonation time and voice intensity was found. In patients prescribed voice rest, a dramatic decrease in voice use, both in phonation percent and sound level was found.
Södersten, Salomao, McAllister, Ternström	2015	20 patients with voice disorders and 10 vocally healthy	f_o, voice and noise SPL, phonation time	2 days	Voxlog. Data from 10 hospitals were sent to a remote central database for analyses. Large variation within and between days. Strict protocols for data collection are needed.
Van Stan, Mehta, Zeitels, Burns, Barbu, Hillman	2015	35 female patients with vocal fold trauma, 35 matched controls	f_o, voice phonation time, vocal dose measures, voicing vs voice rest	1 week	Smartphone-based ambulatory voice monitor. No stat sign differences between patients and controls. More refined characterizations of underlying phonatory mechanisms and other potentially contributing causes are warranted
Gama, Santos, Pedra Ede, Rabelo, Magalhaes Mde, Casas	2016	5 teachers with functional dysphonia and 5 controls	f_o, voice and noise SPL, phonation time, cycle dose	40 minutes during a morning lecture	Voxlog. Higher values of phonation time and cycle dose in teachers with dysphonia than the controls

Mehta, Cheyne, Wehner, Heaton, Hillman	2016	18 (6 patients, 6 matched control group without voice disorders, 6 low voice users)	Phonation time, hourly self-reports of time spent talking	5 days	APM. Participants overestimated their phonation times. Large variations.
Yiu and Yip	2016	12 men, 12 women	f_o, voice and noise intensity, perceived vocal effort	Reading a passage in 3 natural environments under three natural environmental conditions (quiet moderate, and high noise level	APM. Increase of all variables in the high noise environment (> 67 dBA) for both gender groups. No significant difference was found in the voice intensity between the quiet and moderately noisy environment except for f_o in the female group.
Bottalico, Astolfi and Hunter	2017	22 primary school teachers in class -rooms with high vs low RT	RT, f_o, voice SPL	1-2 working days, 4 hour blocks	APM. In high RT (>.90 sec) higher voicing accumulations and higher accumulations of the silences was found suggesting that classroom RT can affect vocal load and lead to vocal fatigue
Bottalico, Graetzer, Astolfi and Hunter	2017	26 primary school teachers (4 with organic, 11 with mild organic or functional voice disorder, and 11 vocally healthy)	Silence and voicing periods	4 hour workdays	APM. Results showed higher time dose for patients with vocal fold lesions. Silence > 3. 16 sec needed for vocal recovery.
Cantor Cutiva, Puglisi, Astolfi, Carullo	2017	27 female teachers	f_o ,Voice SPL, phonation time, RT	1-4 (four-hour) workdays	Voice Care and APM. Voice level and f_o were significantly higher at work than in a conversational setting. Higher voice levels with higher background noise levels. A tendency that noise level increased with increasing RT.
Nusseck, Richter, Spahn, Echternach	2017	113 teachers	f_o, voice and noise SPL, phonation time	1 classroom lecture	Voxlog. Strong correlation between voice SPL and f_o, with the classroom noise level.
Puglisi, Astolfi, Cantor Cutiva and Carullo	2017	27 female primary school teachers	f_o , voice and noise SPL, phonation ratio. Decay time, RT, room gain	Pre monitoring and 1-4 (four-hour) workdays, in average 2.3 days/teacher	Voice care and APM. Teachers with higher variation of voice sound pressure level and phonation time during the pre-monitoring recording reported fewer voice complaints

Schiller, Morsomme, Remacle	2017	13 music theory teachers	f_o, phonation time, voice and noise SPL, vocal loading index (VLI), subjective ratings of voice quality and vocal fatigue	1 workweek	Voxlog. Sign higher vocal loading measures and noise SPL in the professional than in the non-professional environments. Voice SPL, phonation time, and f_o in females correlated positively with noise SPL. Higher noise levels were associated with increased vocal loading. VLI correlated with self-assessed voice quality, vocal fatigue, and amount of singing and speaking voice produced.
Whitling, Lyberg-Åhlander, Rydell	2017	50 teachers with voice problems and controls	f_o, voice and noise SPL, phonation time	7 days	Voxlog. Women with high voice complaints had higher phonation times and f_o at work than controls. Patients experience voice problems permanently, whereas women with everyday vocal load and voice complaints recover during leisure.

APM = Ambulatory Phonation Monitor
Cycle dose = total number of vocal fold vibrations over the measured time
Distance dose = total distance the vocal fold "travel" over the measured time
f_o = fundamental frequency
IPSI = Inability to Produce a Soft Voice
NCVS = The National Center for Voice and Speech
RASTI = Rapid Speech Transmission Index
RT = Reverberation Time
SPL = Sound Pressure Level
VHI = Voice Handicap Index
VLI = Vocal loading index = total number of vocal fold vibrations over time

Table 2. Studies that have used portable DAT-recorders in chronological order from 1994 to 2016.

Authors	Year	Participants	Parameters	Measuring Time	Analyses and main results
Rantala, Haataja, Vilkman, Körkkö	1994	3 female teachers	f_o, SPL, phonation time	First and last lesson during 1 workday	4-minute samples were selected for analyses. Average f_o and SPL were higher in the afternoon compared to the morning. Phonation time was 41% in the morning and 26% in the afternoon.
Rantala, Lindholm, Vilkman	1998a	3 female teachers	f_o, SPL, phonation time	First and last lesson during 1 workday	4-minute samples were selected for analyses. f_o was higher during field conditions than during aloud text reading in a laboratory condition. f_o increased both during loading in the laboratory and at work.
Rantala, Paavola, Körkkö, Vilkman	1998b	10 female teachers	f_o, acoustic spectral metrics, voice complaints	First and last lesson during 1 workday and 3 times each lesson	[a] vowels were used for spectral analysis. There was an increase in the energy content of the high frequency components due to vocal loading. Differences between those who had more vs. less complaints.
Rantala, Vilkman	1999	12 female teachers (2 groups according to few or many voice complaints)	f_o, SPL, phonation time, perturbation, voice complaints	Before and after first lesson, after lunch break and last lesson, during 3 workdays	4-minute samples were selected for analyses at breaks. Teachers with many voice complaints had a higher average f_o and lower SPL, and lower shimmer and jitter values than teachers with few voice complaints. A vocal loading index correlated positively with the subject's voice complaints.
Jonsdottir, Rantala, Laukkanen, Vilkman	2001	3 female teachers, 2 male teachers	f_o, voice SPL, phonation time	First and last lesson during 1 workday, at 2 occasions 1 week apart	4-minute samples were selected for analyses. Recordings were made under ordinary conditions and when using electrical sound amplification. Amplification lowered f_o and SPL, while phonation time was not significantly affected.
Jonsdottir, Laukkanen, Vilkman	2002	5 teachers	f_o ,voice SPL, voice complaints	First and last lesson during 1 workday, at 2 occasions	4-minute samples were selected for analyses. Recordings were made under ordinary conditions and while using electrical sound amplification with a weeks difference. f_o and SPL were higher in the last lesson compared to the morning lesson in both unamplified and amplified conditions. f_o increased statistically more when amplification was used.
Rantala, Vilkman, Bloigu	2002	33 female teachers (2 groups according to few or many voice complaints)	f_o, SPL, phonation time	First and last lesson during 1 workday	4-minute samples were selected for analyses. The most obvious change was the rise of f_o between the first and last lesson. f_o increased more in the subgroup with few voice complaints than the group with many.

Södersten, Granqvist, Hammarberg, Szabo	2002	10 female preschool teachers	f_o, phonation time, voice SPL background noise level	6-8 hours during 1 workday	Analyses were made from recordings during an entire workday using binaural microphones. f_o and voice SPL were significantly higher during the workday as compared to aloud reading in a silent room before work. Background noise varied between the pre-schools; from 73.0 to 78.2 dBA. Average phonation time was 17%.
Lehto, Laaksonen, Vilkman, Alku	2006	24 female customer-service advisors	f_o, voice SPL, cycle dose, alpha ratio	1 workday, 4 x 20 minutes recordings of the telephone conversations	5 minutes per recording were analysed. f_o, and the voice symptoms rose significantly during the working day but no correlations between vocal symptoms and acoustic measures were found.
Lehto, Laaksonen, Vilkman, Alku	2008	24 female and 8 male customer-service advisors	f_o, voice SPL, cycle dose, glottal airflow and acoustic spectral metrics, voice symptoms	1 workday, 4 x 20 minutes recordings of the telephone conversations	5 minutes per recording were analysed. Of all the measures only f_o resulted in a statistically significant increase during the workday for both genders. There were no correlations between the objective and subjective voice data.
Ben-David and Icht	2016	27 call centre operators and 25 age- and gender-matched students	f_o, voice SPL, coefficient of variation, perceptual analyses	Recordings of a reading task at the beginning and end of a workday	Based on a reading task, f_o was higher in the end of the workday for the students but not for the call centre operators, suggesting that the f_o rise is typical but not for persons exposed to vocal loading.
Schloneger and Hunter	2016	19 college and university singing students	Cycle- distance dose, LTAS-slope, alpha ratio, H/N ratio	3 weekdays	Assessments of voice use and voice quality through ambulatory monitoring with a full accelerometer signal. Higher vocal doses correlated with higher voice intensity, more vocal clarity and less perturbations. Differences between singing styles were found.

f_o = fundamental frequency
Cycle dose = total number of vocal fold vibrations during the recorded time
Distance dose = total distance the vocal fold "travel" during the recorded time
H/N = harmonics-to-noise
LTAS = Long-Time Average Spectrum
SPL = Sound Pressure Level
VLI = Vocal Loading Index = total number of vocal fold vibrations during the recorded time

1.1.3 Technical development

The first generation of voice accumulators recorded one or two parameters, and had limited memory capacity that did not allow for recordings longer than a few days. Over the years, the technique has evolved to include devices that can measure both voice use and environmental noise, and give biofeedback, to smartphone-based platforms that can record, store and display voice data in graphic representations for long periods of time, and also integrate subjective voice ratings (Halpern, Spielman, Hunter, & Titze, 2009; Manfredi et al., 2017; Van Stan et al., 2014). The monitors need to be simple to put on and take off, to operate, and to be carried without impact on movements or daily life activities (Nix, Svec, Laukkanen, & Titze, 2007). The technical development has strived for smaller and more lightweight devices, since the early voice accumulators were perceived as quite cumbersome to wear (Hunter, 2012).

Voice accumulators and voice dosimeters enable long-term recordings in field conditions without compromising user integrity, since the content of speech is not recorded. Instead of recording the audio signal, a contact microphone or an accelerometer attached to the neck surface registers the vibrations from the vocal folds (Van Stan et al., 2014). Consequently, the influence of environmental noise on the speech signal is minimized. From the accelerometer signal, voice parameters such as f_o and phonation time as well as voice SPL can be derived (Svec, Titze, & Popolo, 2005). The voice data are processed and stored in a box, usually worn on the waist (Hunter, 2012; Van Stan et al., 2014). Average measures of the voice parameters are stored in form of numbers. The time frames vary from milliseconds, to seconds or minutes depending on the method, task and the duration of the recording.

Some common voice disorders, such as vocal nodules, are believed to be caused by vocal overload. To better understand the actual role of vocal load, more studies monitoring voice use in patients are needed (Bottalico, Graetzer, Astolfi, & Hunter, 2017; Gama et al., 2016; Ghassemi et al., 2014; Södersten, Salomao, McAllister, & Ternström, 2015; Van Stan et al., 2015; Whitling, Lyberg-Åhlander, & Rydell, 2017). A disadvantage of analysing the data in real-time, as in the voice accumulators, is that it is not possible to study the voice signal in detail after the recording. Thus, one cannot investigate post hoc the reason for suspiciously abnormal data; which could be due to unusual phonation patterns, such as might be expected in dysphonic voices. However, the alternative, to record the raw signals and analyse them later, incurs ethical problems of integrity, both for the wearer of the equipment and for people in the surroundings, since the content of speech is not concealed. Also, the analysis post recording can be quite time-consuming, which may be problematic particularly in a clinical setting.

1.2 VOCAL LOADING

Vocal load signifies the quantity of phonatory stress on the vocal apparatus, such as extended duration of phonation, elevated f_o and intensity (Fujiki & Sivasankar, 2017; Horacek, Laukkanen, Sidlof, Murphy, & Svec, 2009; Whitling, 2016; Vilkman, 2004). Vocal loading is also related to hyperfunction (Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1989) and opportunities for voice rest (Hunter & Titze, 2009). Vocal loading tests conducted under laboratory conditions have been designed to identify speakers who are vulnerable to developing vocal pathology (e.g., Echternach, Nusseck, Dippold, Spahn, & Richter, 2014; Whitling et al., 2014). There may be a phase of adequate adaptation to vocal loading, a vocal warm-up effect, before it leads to vocal fatigue (Vintturi et al., 2001). Furthermore, large individual variation as a response to vocal loading has been found in laboratory experiments and in field conditions (Lindström et al., 2011; Whitling et al., 2017; Vintturi et al., 2001). Therefore, the amount of vocal loading an individual can be exposed to before it constitutes a risk to vocal health is likely to vary between individuals. Consequently, defining safety limits for vocal loading has proved to be difficult, since there is no clear linear relationship between amount of vocal loading and the associated risk of phonotrauma (Svec, Popolo, & Titze, 2003; Titze & Hunter, 2015; Vilkman, 2004). In an attempt to more explicitly determine the impact of repeated vocal fold vibrations on the vocal fold tissue, Titze, Svec, and Popolo (2003) proposed several vocal dose types: time dose (total phonation time); cycle dose (total vocal fold vibration cycle); distance dose (total distance that the vocal folds move incorporating f_o, phonation time and voice SPL); energy dissipation dose (total amount of heat created by the vocal folds); and radiated energy dose (total energy emitted by the mouth). The cycle dose is similar to the vocal loading index introduced by Rantala and Vilkman (1999), where f_o is multiplied by the phonation time. An advantage with the distance dose (Titze & Hunter, 2015; Titze et al., 2003), is that it takes into account the impact of the mechanical stress on the vocal folds not only from the number of vocal fold collisions, but also from voice SPL.

1.3 WORK-RELATED VOICE DISORDERS

The voice is essential in oral communication and a crucial tool at work for about one third of the workforce in today's society (Vilkman, 2004). When the voice and the vocal folds are affected by heavy vocal load at work, this can severely affect a person's work ability and psychosocial well-being (Alva, Machado, Bhojwani, & Sreedharan, 2017; Bassi et al., 2011; Behlau, Zambon, Guerrieri, & Roy, 2012; Merrill, Anderson, & Sloan, 2011; Roy, Merrill, Gray, & Smith, 2005). In addition to individual suffering, occupational voice disorders also have a considerable impact on the economy, including costs associated with decreased productivity, sick leave, employee turnover, substitute workers and health care (Verdolini & Ramig, 2001).

1.3.1 Occupational voice user vs. professional voice user

Titze, Lemke, and Montequin (1997) defined professional voice users as "(a) those who depend on a consistent, special, or appealing voice quality as a primary tool of trade, and (b) those who, if afflicted with dysphonia or aphonia, would generally be discouraged in their jobs and seek alternative employment." Vilkman (2000, 2004) proposed to categorize professional voice users according to: (a) voice quality demands (e.g., for singers, actors and TV-presenters the requirement on voice quality is high while for industrial workers it is low); and (b) vocal load (e.g., teachers is a profession with high vocal load and computer programmers a profession with low vocal load). The proportion of people working in professions with high quality demands, such as singers and actors, is rather small (Vilkman, 2000) and they receive extensive voice training during their education to be prepared to perform well so that the voice will be sustained. They can be considered “professional voice users”. A larger proportion of people work in occupations with high vocal load, but with fewer requirements on voice quality, such as teachers and customer call centre workers (Vilkman, 2000). This group can be considered “occupational voice users” and receive usually little or no voice training compared to professional voice users (Manfredi & Dejonckere, 2016).

1.3.2 Work-related voice disorder vs. occupational voice disorder

Voice disorders may be caused by functional factors, i.e. the way the voice is used, such as excessive voice use and tension in the muscles involved in phonation (Koufman & Blalock, 1982). They may also be caused by other factors, such as infections, or a combination of both such as vocal nodules (Fritzell, 1996; Karkos & McCormick, 2009). This thesis focuses on work-related voice disorders, presumably caused by a high vocal load. A voice disorder can be considered work-related when the voice is affected in such way that it does not meet the vocal demands that the work requires, according to Vilkman (2004). Furthermore, a voice disorder can be recognized as an occupational disease if diagnosis and assessment prove that the voice disorder is caused by the job (Dejonckere, 2001). Different countries have different criteria and legislation regarding whether or not a voice disorder can be classified as a work disease (Dejonckere, 2001). In the present thesis, the term “work-related”, and not “occupational”, voice disorder is used in Studies IV and V. The reason is that the patients included in these studies had voice disorders that were considered work-related after clinical assessment by a phoniatrician and a speech-language pathologist. However, the patients’ diagnoses had not been investigated and recognized as an occupational disease by The Swedish Social Insurance Agency. There is a lack of well-defined criteria as to what constitutes an occupational voice disorder in Sweden.

1.3.3 Prevalence of work-related voice disorders

There are several reasons for the large span of reported data on prevalence concerning work-related voice disorders. Firstly, there is a disparity in definitions of “voice disorders”, “voice problems” and “voice symptoms” and, secondly different methods have been used to collect prevalence data. Most studies have used questionnaires (for reviews see: Cantor Cutiva, Vogel, & Burdorf, 2013; and Martins, Pereira, Hidalgo, & Tavares, 2014). Phone interviews have also been conducted (Roy et al., 2005; Roy et al., 2004), and a limited number of studies have based prevalence data on videolaryngoscopic findings (Pereira, Tavares, & Martins, 2015; Preciado-Lopez, Perez-Fernandez, Calzada-Uriondo, & Preciado-Ruiz, 2008; Sala, Laine, Simberg, Pentti, & Suonpää, 2001; Smolander & Huttunen, 2006; Tavares & Martins, 2007). Furthermore, the time frame has varied, and it has not always been clear if it was point prevalence, i.e., currently present, or prevalence based on data from the preceding year, or if lifetime prevalence had been investigated. Frequently quoted numbers come from an American cross-sectional telephone survey with a random sample of 1,326 participants (Roy et al., 2005). In that study, the lifetime prevalence of a voice disorder in the general population was 29.9%, the point prevalence was 6.6%, 4.3% were limited or unable to do certain tasks at work because of voice problems, 7.2% reported one or more days of voice-related absence from work in the preceding year, and 2% reported absence from work of more than four days due to voice problems (Roy et al., 2005). As yet unpublished data from a public health survey in the general population in Sweden revealed that 16.9% of an open cohort of 114,538 adults (response rate 64.9%) reported voice problems that were not due to colds and upper airway infections. 15.5% rated their voice problems to occur to a lesser extent and 1.4% to a greater extent (Lyberg-Åhlander, Rydell, Fredlund, Magnusson, & Wilén, 2015).

The occurrence of voice disorders in occupational voice users is higher compared to that in the general population (Fritzell, 1996; Roy et al., 2004). The research focus has mainly been on teachers (Martins et al., 2014). A systematic review (Cantor Cutiva et al., 2013) reported the following ranges of prevalence numbers in teachers based on 23 publications: (i) point prevalence from 9% (Smith, Lemke, Taylor, Kirchner, & Hoffman, 1998) to 37% (Thomas, de Jong, Cremers, & Kooijman, 2006); (ii) prevalence based on the preceding year from 15% (de Medeiros, Barreto, & Assuncao, 2008) to 80% (Pekkarinen, Himberg, & Pentti, 1992); and (iii) life-time prevalence from 51% (Angelillo, Di Maio, Costa, Angelillo, & Barillari, 2009) to 69% (Sliwinska-Kowalska et al., 2006). In a Swedish study, 13% of the teachers experienced voice problems sometimes, often, or always, and 18% stated that they considered changing work due to voice problem (Lyberg-Åhlander, Rydell, & Löfqvist, 2011). Organic lesions, such as vocal nodules, have been reported in 10% to 31% of teachers (Pereira et al., 2015; Preciado-Lopez et al., 2008; Sala et al., 2001; Smolander & Huttunen, 2006; Tavares & Martins, 2007). In comparison, vocal nodules were found in only 2% of nurses (Sala et al., 2001). Professions with a reported high point prevalence are for example aerobics instructors, 27% (Kersner, 1998), and priests, 27% (Hagelberg & Simberg, 2015).

The number of studies investigating prevalence and risk factors for voice disorders in different professions has increased steadily during the last two decades. However, there is little support to conclude that voice problems per se are increasing in occupational voice users, due to methodological disparity and the lack of longitudinal studies. One instrument needs to be used consistently in order to compare data in a meaningful way and judge if voice problems have increased in a population or not. There are currently no standardized instruments to measure voice symptoms. However, in Finland, several studies have been conducted using the same screening instrument over time (e.g., Simberg, Sala, Laine, & Rönnemaa, 2001). One study revealed that the prevalence of voice symptoms occurring weekly or more often in teachers more than doubled during a 12-year period and increased from 12% to 29% of teachers affected (Simberg, Sala, Vehmas, & Laine, 2005). Another study by Sala et al. (2001) showed that the prevalence of voice symptoms among hospital nurses doubled in 10 years, increasing from 7% to 14% of those studied reporting problems. Furthermore, those who reported two or more frequently occurring vocal symptoms often had visible changes on their vocal folds (Sala et al., 2001).

1.3.4 Gender differences

Women are in general more affected by vocal health issues than men, especially women with vocally-demanding and highly communicative professions (Fritzell, 1996; Hunter, Tanner, & Smith, 2011; Lyberg-Åhlander et al., 2015; Morton & Watson, 1998; van Houtte, Claeys, Wuyts, & van Lierde, 2012; Van Stan et al., 2015). In the general population, compared to men, women were found to report a history of voice problems nearly twice as often (Roy et al., 2005), and in another study, organic lesions were three times more frequent in women (Preciado-Lopez et al., 2008). A report from the European Agency for Safety and Health at Work (2013) recognized that a substantial proportion of women in nonindustrial and communication-demanding workplaces, for example within education, healthcare and customer call centres, suffers from voice problems. Women in vocally-demanding professions are at an especially high risk of developing functional voice disorders, such as phonasthenia and vocal nodules (Fritzell, 1996; Titze et al., 1997). In the study by Fritzell (1996), 33% of patients (N = 1,212) had phonasthenia and 16% had vocal nodules. Of those, 72% of the patients with phonasthenia and 97% of the patients with vocal nodules were women. The fact that work-related voice disorders are more common in women was the reason to include only female participants in the Studies III-V in the present thesis.

Causality factors for the higher incidence of voice problems in women include anatomical and physiological differences between men and women in the laryngeal and respiratory systems (Titze, 1989b), hormones, and psychosomatic and behavioural characteristics (see Hunter et al., 2011 for a review). A reason for the female voice to be more vulnerable to vocal loading compared to the male voice is that women's vocal folds are about 60% shorter and 20% to 30% thinner than male vocal folds (Titze, 1989b). Consequently, with roughly double the f_o compared to men, women are exposed to a larger amount of mechanical stress on the vocal folds. Furthermore, women have in their vocal folds a smaller content of hyaluronic acid, which provides shock absorption. The female voice may therefore be more vulnerable to vocal fold injury (Butler, Hammond, & Gray, 2001). Other common risk factors in patients with voice disorders, with higher incidence in females than in males, are stress, anxiety, and depression (Dietrich, Verdolini Abbott, Gartner-Schmidt, & Rosen, 2008; Holmqvist, Santtila, Lindström, Sala, & Simberg, 2013; Misono, Meredith, Peterson, & Frazier, 2015; Ng, Lo, Lim, Goh, & Kanagalingam, 2013). Another gender difference is that the female voice seems to be more at risk when speaking in high environmental noise levels. In studies by Ternström, Bohman, and Södersten (2006) and Södersten et al. (2005) women produced 3-5 dB lower voice SPL compared to men in a given noise level, presented as realistic environmental noise over loudspeakers, and the female participants reported a greater difficulty in making themselves heard.

1.3.5 Phonastenia

Phonasthenia is a functional voice disorder where the laryngeal status is normal (Fritzell, 1996). The predominant symptom is vocal fatigue. Vocal fatigue is believed to be caused by excessive muscular tension in the vocal folds and larynx (Solomon, 2008). Furthermore, phonasthenia is characterized by diffuse and various symptoms of discomfort in and around the throat (Holmberg, Ihre, & Södersten, 2007). The resulting voice quality can vary from being normal sounding to more dysphonic (Holmberg et al., 2007). Apart from vocal fatigue, patients with phonasthenia frequently report strain and difficulties in projecting the voice. Due to a weak and unstable voice, patients also report difficulty in making themselves heard in noisy environments. The consequence is often an inability to meet the vocal demands of a vocally-demanding occupation.

1.3.6 Vocal nodules

Vocal nodules is a functional-organic voice disorder. The nodules are benign bilateral epithelial swellings of the vocal folds. They are believed to arise after prolonged mechanical friction on the vocal fold mucosa (Gray, Hammond, & Hanson, 1995; Karkos & McCormick, 2009) due to vocal overload and hyperfunction, such as extensive voice use and insufficient voice rest, in combination with high levels of voice SPL or f_o (Czerwonka, Jiang, & Tao, 2008; Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1990; Holmberg, Doyle, Perkell, Hammarberg, & Hillman, 2003; Holmberg, Hillman, Hammarberg, Södersten, & Doyle, 2001; Karkos & McCormick, 2009). Hoarseness is the predominant associated voice symptom together with strain and instability. The nodules obstruct complete vocal fold closure, which results in a breathy and weak-sounding voice. Because this in turn may lead to compensatory increased subglottal pressure and hyperfunction, it has been described as a “vicious circle” since the augmented vocal fold collision forces add to the trauma and preserves the nodules (Hillman et al., 1989; Hillman et al., 1990). Excessive voice SPL is common among patients with vocal nodules (Holmberg et al., 2003; Holmberg et al., 2001). Patients with vocal nodules have also been found to use significantly higher subglottal pressure than vocally healthy controls despite the same voice SPL (Aronsson et al., 2007). Like for patients with phonasthenia, the symptomatology makes it hard for patients with vocal nodules to achieve vocal demands in voice intensive jobs.

1.3.7 Voice symptoms

Subjectively reported voice data and ratings of voice symptoms enable the ability to get patients’ perceptions of their voice as well as fluctuations over time. Numerous studies have included questions about voice symptoms in study-specific questionnaires, with a focus on prevalence of voice problems and risk factors for voice disorder, whereas only a few studies have collected information about variations in voice symptoms over time (Cantor Cutiva, Fajardo, & Burdorf, 2016; Lehto et al., 2006, 2008). For example, voice symptoms for customer call centre workers increased during the workday (Lehto et al., 2006, 2008). Weekly fluctuations have been reported for preschool teachers and teachers with an increase in voice symptoms at the end of a workweek, and a decrease during weekends and holidays, because of fewer vocal demands (Sala et al., 2001; Smolander & Huttunen, 2006). Common symptoms that have been reported for individuals with vocally-demanding professions such as teachers and preschool teachers (Bermúdez de Alvear, Barón, & Martínez-Arquero, 2011; Lyberg-Åhlander, Rydell, & Löfqvist, 2012; Ohlsson, Andersson, Södersten, Simberg, & Barregård, 2012; Pekkarinen et al., 1992; Sala et al., 2001; Smolander & Huttunen, 2006); aerobics and fitness instructors (Kersner, 1998; Rumbach, 2013); customer call centre workers (Jones et al., 2002; Lehto et al., 2008); priests (Hagelberg & Simberg, 2015) are vocal fatigue, hoarseness, throat clearing, a sensation of pain or lump in the throat, and difficulties to make oneself heard. To understand the origin of the voice disorder, a reliable estimation of how much, and how, the voice is used is needed (Vilkman, 2004). The validity and reliability of the self-ratings by patients with work-related voice disorders have, however, been disputed since occupational voice users may lack awareness of how much they talk and of fluctuations in voice symptoms over time (Bastian, Keidar, & Verdolini-Marston, 1990; Karnell et al., 2007; Mehta, Cheyne, Wehner, Heaton, & Hillman, 2016). Furthermore, subjective symptoms, e.g., vocal fatigue and hoarseness, have not been found to correlate significantly with instrumentally measured voice data, e.g., f_o and voice SPL (Laukkanen, Ilomaki, Leppanen, & Vilkman, 2008; Lehto et al., 2008). How patients with work-related voice disorders perceive their voice use, and how voice symptoms correspond with instrumental measurements over time is, however, of interest both from research and clinical perspectives, and needs further attention.

1.3.8 Voice qualities

The effect of work-related voice disorders, such as phonasthenia and vocal nodules, on voice quality can be anything from unnoticeable, to mild or severe (Dejonckere, 2001; Manfredi & Dejonckere, 2016; Vilkman, 2004), and includes voice qualities such as breathy, strained, creaky, rough and hoarse (Hammarberg, Fritzell, Gauffin, Sundberg, & Wedin, 1980; Holmberg et al., 2003; Holmberg et al., 2007). Breathy voice quality is when air passes through the glottis due to incomplete vocal fold closure during phonation, e.g. because of the presence of vocal nodules, creating turbulence and noise. A strained voice sounds effortful and is the result of hyperfunction and excessive muscle contractions in the larynx. Creaky voice is supposed to resemble the sound of a creaking door, and is the result of a complex vibration pattern of the vocal folds and presence of subharmonics in the acoustic spectrum. The term hoarseness can be used to describe the combination of breathiness and roughness characterized by irregular phonation patterns (Hammarberg et al., 1980; Titze, 1995).

1.4 RISK FACTORS

Work-related and individual risk factors associated with voice disorders are shown in Table 3.

Table 3. Work-related risk factors and risk factors related to the individual, adapted after Vilkman (2004).

Work-related risk factors	Risk factors related to the individual
Extensive voice use	Gender
Loud speaking voice	Age
Environmental noise	Voice problems during childhood
Poor room acoustics	Health condition
Long speaking distance	Allergies
Insufficient time for voice rest	Asthma
Stress	Smoking
Dry air, dust, chemicals	Stress
Work posture	Anxiety
No access to voice amplification	Number of years working
	Personality
	Life habits
	Awareness
	Coping strategies
	Self-care behaviours
	Insufficient pre-professional voice training

Predisposing genetic factors for voice disorders have been described in the literature (Hirschi, Gray, & Thibeault, 2002; Nybacka, Simberg, Santtila, Sala, & Sandnabba, 2012; Roy et al., 2004; Simberg et al., 2009; Thibeault, Hirschi, & Gray, 2003). Yet, it seems that environmental factors have a stronger influence on the development of voice disorders than genetic factors (Nybacka et al., 2012; Rantala, Hakala, Holmqvist, & Sala, 2012; Simberg et al., 2009). Why some individuals more than others are prone to developing a voice disorder, despite similar working conditions and vocal load need to be further explored. For example, individual factors such as health conditions, life habits, personality traits and psycho-emotional factors influence how individuals cope with vocal load (Kooijman et al., 2006; Oliveira, Hirani, Epstein, Yazigi, & Behlau, 2012; van Houtte et al., 2012). The work-related risk factors that are investigated and included in the present thesis appear in Table 3 highlighted in bold, i.e., extensive voice use, habitually loud speaking voice and environmental noise.

1.4.1 Environmental noise

Women with voice intensive occupations often work in environments with high noise levels. How vocal behaviour and vocal health are affected for individuals who need to speak in high levels of background and activity noise in daily life is relatively unexplored (European Agency for Safety and Health at Work, 2013; Kristiansen et al., 2014; Rantala, Hakala, Holmqvist, & Sala, 2015). High noise levels around and above 70 dBA are common in many communication- and vocally-demanding workplaces such as schools and preschools (Shield et al., 2015; Sjödin, Kjellberg, Knutsson, Landström, & Lindberg, 2012). To enhance the audibility of the voice in loud environmental noise, the speaker typically increases the voice SPL, along with increased f_0 which may result in hyperfunction (Garnier & Henrich, 2014; Hillman et al., 1989; Holmberg et al., 2003; Södersten et al., 2005; Titze, 1989a; Yiu & Yip, 2016). A systematic review by Cantor Cutiva et al. (2013) revealed that high environmental noise levels, and the use of high voice SPL, are among the most common risk factors for voice disorders in teachers. The report from the European Agency for Safety and Health at Work (2013) showed that there is a lack of research on the effects of occupational noise exposure on health in non-industrial and communication-demanding workplaces; environments that often have a high proportion of employed women. However, within education, healthcare, customer call centres and offices, it is not the stationary noise levels that disturb the most; rather it is the occasional high levels of environmental noise caused by activity, such as voices and other sounds from people in the surroundings. Activity noise disturbs speech communication and may interfere with performance and wellbeing (Astolfi & Pellerey, 2008; Banbury & Berry, 2005; Lundquist, Holmberg, & Landström, 2000; Shield & Dockrell, 2008). To maintain speech intelligibility, and to avoid the speaker having to increase voice SPL, conversation should be kept below 50-55 dBA (Yiu & Yip, 2016). Increased voice SPL is required at 70 dBA, and at 80-85 dBA the speaker must shout to be heard at 1 meter (Arlinger, 1999; The Swedish Work Environment Authority's provisions for noise, AFS 2005:16). According to the Swedish Work Environment Authority's report on work environment statistics for 2015 (Report 2016:2), 58% of preschool teachers (exclusively women) are exposed to noise levels so high that they cannot make themselves heard without raising voice SPL during at least one quarter of the working time.

2 AIMS OF THE THESIS

The overall aims were to evaluate methods for long-term voice accumulation and to assess female voice use in vocally-demanding professions.

The specific aims were:

- to evaluate a voice accumulator's (VACLF1) two software for registration of f_o and phonation time compared to simultaneous studio recordings, and to test it in field recordings (Studies I and II);

- to evaluate the voice accumulator's (VACLF1) registration of f_o and phonation time compared to simultaneous audio recordings when voice quality, fundamental frequency and loudness varied in a systematic way (Study II);

- to determine whether f_o and phonation time differed between work and leisure time, and describe variations in f_o and phonation time across the workday, in preschool teachers with healthy voices (Study III);

- to investigate voice use in women with vocally-demanding professions to see if there were differences in voice use (1) between patients with work-related voice disorders and vocally healthy controls, and (2) between work and leisure conditions, with environmental noise level as an experimental factor (Study IV); and

- to investigate variations in subjective voice symptoms and voice use during one week in women with vocally-demanding professions, and to see (1) if there were differences between individuals with and without voice disorders, (2) if there were differences between work and work-free days, and (3) if patients with voice disorders and vocally healthy individuals were able to give reliable feedback on their voice use during days in natural work and leisure situations (Study V).

3 MATERIALS AND METHODS

3.1 PARTICIPANTS

Data for Studies I-III were collected during 1998-2002, and data for Studies IV and V during 2011-2015. The participants in Studies IV and V were the same (Table 4).

Table 4. Summary information about recording conditions and the participants' gender and age for each study.

Study	Recording condition	Participants	Age range
I	Laboratory	2 females, 2 males [1)]	26 - 58 years
	Field	2 females, 2 males [1)]	26 - 51 years
II	Laboratory	1 female	43 years
	Field	3 females [2)]	24 - 26 years
III	Field	12 females [2)]	21 - 53 years
IV	Field	40 females [3)]	21 - 63 years
V	Field	40 females [3)]	21 - 63 years

[1)] In Study I, one female and one male from the laboratory condition also participated in the field condition.

[2)] Two participants from the field condition in Study II were also participants in Study III.

[3)] The participants in Study IV and V were the same.

3.1.1 Study I

Employees at Karolinska Institutet, Stockholm, volunteered as participants. They had no known voice disorder and were non-smokers. In the laboratory condition, two men and two women participated. Two of the participants were working in voice-care professions, one as a phoniatrician, and the other as a speech-language pathologist. Of the other two participants, one was a research engineer and one a secretary. In the field condition, the participants were two women, working as speech-language pathologists, and two men, working as research engineers. One man and one woman participated in both recording conditions.

3.1.2 Study II

One female speech-language pathologist participated in a laboratory recording. She had received voice training, and was able to control her voice according to the test protocol. Two vocally healthy preschool teachers and one professional child minder participated in the field condition. Henceforth, the term "preschool teachers" will be used for both preschool teachers and professional child minders.

3.1.3 Study III

Twelve women with no known voice disorders participated in the study. They each worked at one of six daycare centres in the Stockholm area, randomly selected to represent different socioeconomic areas. The directors of these centres were contacted by a letter and by telephone, and they, in turn, informed the preschool teachers about the study. Two of the participants from the field condition in Study II were also included in Study III.

3.1.4 Studies IV and V

Forty women with vocally-demanding professions took part in Studies IV and V; 20 were patients with work-related voice disorders and 20 were vocally healthy controls. The patients were recruited consecutively from waiting lists for voice assessment by a speech language pathologist, mainly at Karolinska University Hospital, in Stockholm, Sweden. The patients had been diagnosed by a phoniatrician or an ear, nose and throat (ENT) physician before referral to the speech language pathologist. Ten of the patients had received the diagnosis phonasthenia and 10 vocal nodules. Based on the information from the patient history, the speech language pathologist further evaluated if the voice disorder was work-related. Each patient was matched regarding age, occupation, and workplace to a vocally healthy female colleague. An experienced phoniatrician at an ENT-clinic conducted a new videolaryngostroboscopic examination of the patients to confirm the diagnosis, and of the controls to exclude vocal fold lesions. Inclusion criteria were that the participants were older than 18 years of age and did not have a self-reported hearing impairment. Exclusion criteria were singing professionally or regularly in choirs, or previous voice training. The patients with vocal nodules, who had a mean age of 34 years, were significantly younger than the patients with phonasthenia, who had a mean age of 47 years ($P = 0.023$). The age difference likely reflects the clinical incidence.

3.2 VOICE MONITOR SYSTEMS

Three different voice monitor systems were used within the thesis project. A voice accumulator named VACLF1 that measured f_o and phonation time (Håkansson, 1994; Håkansson, 1995) was evaluated in Studies I and II, and was used for data collection in Study III. VACLFI is henceforth called VAC. Audio recordings with a portable DAT recorder were used in Study II to evaluate and compare the voice data from the VAC with. A more recent voice accumulator, VoxLog (Sonvox AB, Umeå, Sweden), was used for data collection in Studies IV and V. In addition to f_o and phonation time, VoxLog also measured the SPLs of the user's voice and of the environmental noise (Wirebrand, 2011, 2012).

3.2.1 Voice accumulator VACLF1

The VAC was designed by Alf Håkansson, engineer at the Department of Logopedics and Phoniatrics at Karolinska Institutet, Stockholm, Sweden (today the Department of Clinical Science, Intervention and Technology, Division of Speech and Language Pathology). The VAC design was inspired by another early prototype of a voice accumulator (Ohlsson, 1988; Ohlsson et al., 1989). The VAC consists of a microprocessor that accumulates information about f_o and phonation time. A contact microphone attached to the front part of the neck (Figure 1) registered skin vibration generated by the vocal folds. An analogue part amplified and filtered the signal, and a digital part analyzed, calculated and stored statistics regarding f_o and phonation time. After amplification, the contact microphone signal was high-pass filtered (HP 100 Hz) and low-pass filtered (LP 1000 Hz). To reduce the risk of capturing harmonics instead of the f_o a method based on time-domain "double-peak-picking" was used (Dolansky, 1955).

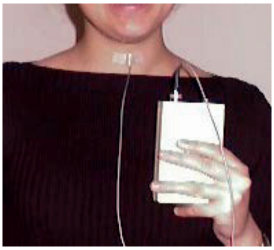

Figure 1. VACLF1.
A contact microphone was attached with adhesive tape to the front of the neck below the cricoid cartilage. The base unit measurements were 144 x 71 x 33 mm. The weight with batteries was 250 grams.

The VAC had two software. One was optimized for measuring f_o (VACF0), and the other was optimized for measuring phonation time (VACPT). In VACF0 the f_o range was unlimited. In order for a sequence to be detected as phonated and included in calculations of f_o averages and phonation time, adjacent period durations were allowed to differ no more than 25%. Influences from artifacts were thereby minimized, because large differences in period durations, not likely originating from vocal fold oscillation, were excluded. In VACPT, all periods were accepted in the f_o range of 60 - 400 Hz. A Microsoft Windows application, VAC Monitor (Håkansson, 1994), was used to initiate the measurements and to export data from the VAC to a spreadsheet (Microsoft Excel), for further calculations and analysis.

3.2.2 Binaural Digital Audio Tape (DAT) method

A binaural microphone technique was used in combination with a portable DAT recorder (Sony TCD-D 100) in Study II. The method was originally developed by a research engineer at KTH - Royal Institute of Technology, Stockholm, for studies of sound intensity in choral performances (Ternström, 1994; Ternström, 1999). Two electret condenser microphones for airborne signals were placed close to the participant's ears at an equal distance from the mouth (Figure 2). Consequently, it was possible to separate the participant's voice from the background noise in stepwise acoustic analysis (Granqvist, 2003). The method and the analysis procedures were further developed by Granqvist (2003) and were applied in studies of preschool teachers' voice use at work (Södersten et al., 2002).

Figure 2. The two microphones were placed close to the ears and fastened with adhesive tape. The DAT recorder's base-unit measures were 78 x 115 x 25 mm. The weight with batteries was 365 grams.

The audio signals were first recorded onto digital audio tape and then transferred onto a computer for analysis. The analysis was based on the assumption that the participant's voice was equally or nearly equally recorded by the left and the right microphones. In contrast, the background noise, which is the sum of many asymmetrically located and non-coherent sound sources, results in differing signals in the two microphones. After separation of the participant's voice and background noise, measurements were made of f_o, phonation time and SPL of the voice of the person who wore the equipment, as well as of the environmental noise level. With this method, the actual speech was recorded, so special considerations had to be made to secure the ethical integrity of the participants and their entourage. In Study II only f_o and phonation time were analyzed for comparison with the VAC data.

3.2.3 VoxLog

VoxLog (Sonvox AB, Umeå, Sweden) consists of a lightweight box containing the hardware and a collar with an accelerometer and a microphone (Figure 3). The device used for this study had firmware at revision 2.2.3. Two types of collar were used. The first had the microphone and the accelerometer placed at separate ends. It was later replaced by an adjustable collar with the accelerometer and the microphone placed in the same end (Figures 3A and 3B).

The accelerometer registered skin acceleration at the neck generated by vocal fold vibrations. Fundamental frequency (f_o in Hz) and phonation time (hours) were derived from the accelerometer signal. SPL of the voice and environmental noise (dB or dB(A)) were derived from the microphone signal. When the accelerometer detects phonation, the SPL registered by the microphone was assumed to originate from the voice of the person who wore the VoxLog. When there was no phonation, the SPL was classified as environmental noise (Wirebrand, 2011, 2012). In this way, the user's voice was separated from the environmental noise (Lindström et al., 2011), similar to the DAT method described above. The microphone was calibrated for SPL by the manufacturer (Sonvox AB), and therefore, no further calibration was needed. The software VoxLog Connect 3.1.13 was used to initiate recordings, to export data onto a computer and for analysis.

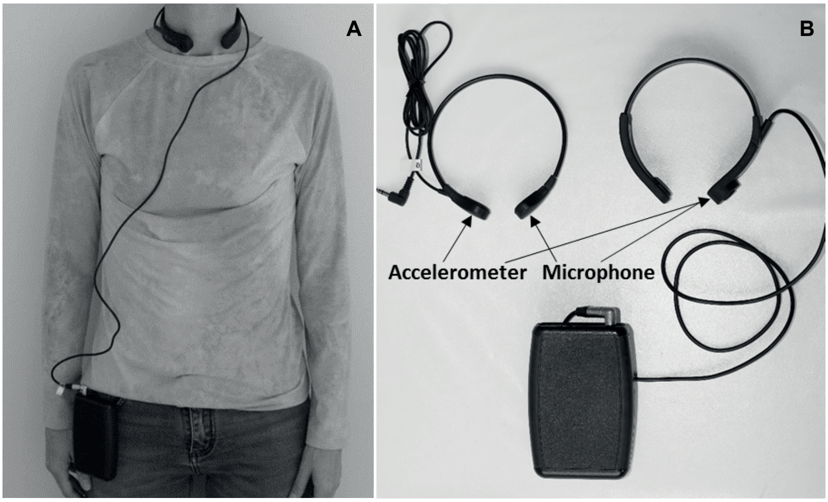

Figure 3. The VoxLog box (90 × 60 × 15 mm) was connected with a wire to a neck collar. The collar used initially had the accelerometer and microphone placed at separate ends. It is shown to the left in Figure 3B. The newer adjustable neck collar, with the accelerometer and microphone placed at the same end is shown to the right. When used in studies IV and V the wire was under the sweatshirt.

3.3 SELF-REPORTS

In conjunction to the field recordings over two days in Study III, the participants responded to statements and questions using 100 mm Visual Analogue Scales (VAS) about voice problems at present and in the past, the noise level at work, difficulties in making themselves heard at work, the amount of voice use during the day, and their experience of the recording equipment. Study-specific self-reports were used also in Study V. In conjunction to the field recordings, the participants rated degree of vocal fatigue, hoarseness, perceived disturbing noise and estimated speaking time, each on a 100 mm VAS, four times a day over one week. The extremes were “not at all” (0 mm) and “a lot” (100 mm). Furthermore, in Studies III-V the participants completed short diary notes of daily activities in relation to voice use, including if they were at work, at home, or elsewhere. The participants in Studies IV and V, furthermore, completed the Swedish-language validated version of the Voice Handicap Index (VHI) (Ohlsson & Dotevall, 2009); VHI-Throat (Lyberg-Åhlander, Rydell, Eriksson, & Schalen, 2010); Swe-VAPP, which is the Swedish translation of the Voice Activity and Participation Profile (VAPP) (Elofsson & Lind, 2005; Ma & Yiu, 2001).

3.4 PROCEDURES

3.4.1 Study I

The study was divided into two parts; a laboratory condition and a field condition. In the laboratory condition, simultaneous recordings were made in a sound-treated booth with one contact microphone with input to the VAC and a second contact microphone with input to a computer. The contact microphones were attached with adhesive tape to the front of the participant’s neck. To ensure proper placement, the microphones were also connected to an oscilloscope, for monitoring and detection of adequate vocal fold vibrations. The participants read aloud a standard text lasting approximately 45 seconds. The signal onto the computer was recorded with a data-acquisition program Soundswell (Neovius Data and Signal system AB, Sweden, formerly Hitech Development AB). The recordings were made twice with one of each of the VAC's two software, one optimized for measurements of f_o and the other for phonation time. The detection interval was set to 50 milliseconds and the storage interval to 1 second. The detection interval is the time frame in which the VAC detects periods of f_o. If the sum of the period-times exceeds half of the detection interval, phonation is considered to have occurred. The storage interval is the time frame in which the VAC averages and stores data relating to f_o and phonation time (Håkansson, 1995).

Recordings were also made with the VAC's software optimized for measurements of phonation time (VACPT) during a workday between 8 and 11 hours. In the field condition the detection interval was set to 200 milliseconds and the storage interval to 6 seconds.

3.4.2 Study II

This study was also divided into two parts; a laboratory condition and a field condition. In the laboratory condition, simultaneous recordings were made with the VAC and the binaural DAT method in a sound-treated booth. One participant read a standard text, approximately 30 seconds long. The text was read four times with different voice qualities: (1) normal voice, (2) breathy voice, (3) strained (pressed) voice, and (4) creaky voice (vocal fry). She also sustained the vowel /a/ several times, with approximately 5 seconds' duration each time, and with: (1) increasing f_o in an A-major scale (A≈220 Hz; c#1≈280 Hz; e1≈330 Hz; a1≈440 Hz), and (2) with increasing voice SPL (soft, moderate, and loud) with constant f_o (c#1≈280 Hz).

In the field condition, 3 participants were recorded with the VAC and the binaural DAT method simultaneously during a workday for 7 to 8 hours. The participants wore the VAC and the DAT recorder in a bag attached to the waist. The VACF0 program was used with the detection interval set to 200 milliseconds and the storage interval set to 6 seconds. The batteries for the DAT recorder had to be changed every 1½-2 hours. The research administrator also checked every 2 hours that the microphones were still attached to the skin; otherwise, new adhesive tape was used.

3.4.3 Study III

In this study the participants' f_o and phonation time were recorded with the VAC over two days, both at work and after work during leisure time. The VACF0 program was used with a detection interval of 200 milliseconds and a storage interval of 6 seconds. The average total recorded time was 12 hours per day (range 11 to 14 hours). The research administrator met with the participants in the morning to start the recording and again in the afternoon to verify that the equipment was working correctly.

3.4.4 Studies IV and V

The participants were the same in Studies IV and V. A one-week field registration of f_o, phonation ratio (i.e., the phonation time divided by the total recording time), and SPL of the voice and background noise was conducted using the VoxLog system. The majority of the participants were recorded with a time frame of 5 seconds whereas 4 participants, in the early stage of the project, had been recorded with a time frame of 60 seconds. The research administrator met with the participants at least once during the week of the recording to control the equipment. During that week the participants also completed subjective ratings concerning vocal fatigue, hoarseness, disturbing noise and estimated speaking time, each on a 100 mm VAS, four times per day.

Prior to the field recording, the participants' voices were recorded in a sound-treated booth following a standard procedure that included reading aloud, with and without noise exposure at 70 dBA presented in headphones and a voice range profile. To acquire a baseline recording the participants' voices were simultaneously recorded with the VoxLog using a time frame of 100 milliseconds to ensure that the Voxlog registred voice data correctly.

3.5 ANALYSIS

3.5.1 Study I

The data were transferred from the VAC onto a computer and a spreadsheet (Microsoft Excel). Arithmetic means of f_o and phonation time, expressed in seconds and as a percentage of total analyzed time, were calculated for each interval of text reading as well as for the workday. In order to observe variations in f_o and phonation time during the workday, data were divided into different intervals with reference to (1) phonation time, i.e., the actual time during which the vocal folds vibrated, and (2) registration time, i.e., the total recording time, in other words, how long the participants wore the VAC during the day.

The Soundswell program was used for f_o extraction of the contact microphone signal recorded onto a computer under laboratory condition. The input signal were first high- and low-pass filtered. The HP filter was set to 50 Hz for the male participants and 150 Hz for the female participants. The LP filter was set to 150 Hz for the male participants and 250 Hz for the female participants. A threshold setting, used to separate phonation from noise, was adjusted for each analysis because of differences in phonation pattern between individuals. For each interval of text reading f_o was extracted. Visual inspections and comparisons of the input signal and the f_o contour were made for optimal analysis. Phonation time was calculated in seconds from the results of the f_o extraction by multiplying the percentage of registered f_o in each interval by the duration of the interval. Analysis of f_o and phonation time were made of the whole interval of text reading (about 45 seconds) as well as of every second individually.

3.5.2 Study II

VAC data from the laboratory recording were transferred to a spreadsheet for calculations of arithmetic means of f_o and phonation time, expressed in seconds, for each interval of text reading, and for the sustained vowels. From the field recordings, arithmetic means of f_o and phonation time, expressed as a percentage of total analyzed time, were calculated for four intervals during the workday, corresponding to the duration of the simultaneous DAT recordings of 1½-2 hours, to allow for comparisons between the methods.

The DAT recordings from the laboratory and field conditions were transferred onto a computer using the Soundswell program. Prior to the f_o extraction of the field recordings the participants' voices were separated from the background noise by means of a custom-made computer program named "Aura". The procedure is described by Granqvist (2003) and Södersten et al. (2002). The f_o extraction tool in the Soundswell program was used for f_o extraction of each interval of text reading, and for the sustained vowels, as well as for the 1½-2 hour long recordings at work. Each workday consisted of four recordings of 1½-2 hours each. The cut off frequency for the LP filter was increased manually in cases of high f_o. Typically, the LP filter cut off was set to about 50 Hz above the mean f_o value. Some experimenting with the LP and HP filter settings was made to obtain a maximally stable f_o curve. A threshold setting used to separate phonation from noise was adjusted for each analysis because of differences in phonation pattern between individuals. Visual inspections and comparisons of the acoustic microphone signal and the f_o contour were made to confirm optimal analysis. Phonation time was calculated in seconds from the results of the f_o extraction by multiplying the percentage of registered f_o in each interval by the duration of the interval, and subsequently converted to a percentage of total analyzed time.

3.5.3 Study III

VAC data from the two days of field recordings were transferred to a spreadsheet for calculations of the arithmetic mean of f_o and phonation time, expressed as a percentage of total analyzed time. In order to observe variations in f_o and phonation time during the days, data were divided into one-hour intervals with reference to registration time. In addition, data were analyzed from four-minute intervals taken from three different points in time during the workday. This procedure was used by Rantala and Vilkman (1999) in their study of school teachers' voice use during work: i.e. after one hour, in the middle of the workday, and one hour before the end of the workday.

3.5.4 Study IV

Data from the field recordings were exported from the VoxLog to a computer with the software program VoxLog Connect. This program was also used to categorize data into morning, first and second half of the workday, evening and work-free leisure days, based on the participant's diary notes. Data were visually inspected to check for obvious erroneous parts of the recordings (e.g., due to a malfunctioning microphone). Those parts were manually excluded from the analysis. Subsequently the data were exported as text files for further processing in MATLAB

(R2012a, The MathWorks Inc., Natick, MA, USA). MATLAB is a software for applied numerical analysis. Average measures were calculated for an equivalent continuous level (Leq) of the voice (L_{eqV}) and environmental noise (L_{eqN}), f_o, phonation ratio, noise exposure time, phonation time in noise, and self-to-other ratio (SOR) (dBA). The voice SPL values derived with VoxLog were the level at the microphone placed at the neck. This level is about 7.2 dB higher than at the standard microphone distance of 30 cm (Wirebrand, 2012). The voice SPL values were, therefore, reduced by 7.2 dB, to facilitate comparisons with other studies. Self-to-other ratio was calculated as the difference between the uncompensated voice level at the neck (i.e., not reduced by 7.2 dB) and the environmental noise level (Granqvist, 2003; Ternström, 1999).

Data were sorted into three noise levels using MATLAB; low (Lb≤55 dBA), moderate (55<Lb≤70 dBA), and high (Lb>70 dBA). Thus, calculations were made of L_{eqV}, f_o, phonation ratio, noise exposure time (i.e., recorded hours in low, moderate and high noise level) and SOR in relation to the three ranges of environmental noise level. These level ranges were chosen in accordance with the Swedish Work Environment Authority's regulation about noise (AFS 2005:16) of relevance for voice use. Below 55 dBA the speaker does not need to increase voice SPL to be heard at 1 meter whereas, above 70 dBA, an increased voice SPL is required (Arlinger, 1999). Data from the first and second half of the workday were grouped into the condition "work" and data from morning, evening and work free leisure days were grouped into the condition "leisure".

3.5.5 Study V

In this study self-ratings and the instrumental voice and noise data were divided into five workdays (1-5), and two work-free days (6-7). In most cases workday 1 corresponded to a Monday and workday 5 corresponded to a Friday. The first day with no work (6) corresponded in most cases with a Saturday and the second day (7) with a Sunday. The self-ratings consisted of a total of 4,480 VAS scores (4 parameters x 4 times per day x 7 days x 40 participants). Ninety-six percent of the self-ratings were completed and those were entered into a spreadsheet (Microsoft Excel).

On average, 95 hours were recorded with VoxLog per participant, which equals an average of 13.5 hours per day. The actual amount of analyzed time was less, 12.5 hours per day (93% of the total recordings), because of breaks when some participants did not use VoxLog such as during physical exercise or due to technical errors. The software VoxLog Connect was used to download the data from VoxLog onto a computer and for analysis. In contrast to the procedure in Study IV, the voice SPL values were left uncompensated, i.e., they were not reduced by 7.2 dB. Based on the participant's diary notes, the data were categorized into four time intervals per day, in order to correspond to the time of the subjective ratings for each participant; (1) morning until beginning of workday; (2) beginning of workday until lunchtime; (3) after lunch break until end of workday; and (4) end of workday until bedtime. Comparisons were made between workdays and work-free days. Leisure time before and after work during the workdays was included in the workday analysis. Thus, the categorization differed from Study IV, in which comparisons were made between work condition (corresponding to interval 2 and 3) and leisure condition (corresponding to interval 1, 4 plus work-free days).

3.5.6 Statistical analysis

Statistical analysis was conducted using SPSS Statistics for Windows (Version 23.0, IBM Corp, Armonk, NY, USA) and Microsoft Excel. The rejection level was set to $P < 0.05$ in all analyses. Descriptive statistics were calculated in the five studies. The statistical tests used are presented in Table 5.

Table 5. Statistical tests used in Studies I-V.

Statistical test	**Studies**				
	I	**II**	**III**	**IV**	**V**
Independent t-test					x
Mann-Whitney U Test					x
Dependent t-test			x		x
Wilcoxon Signed-Rank Test					x
One-way ANOVA					x
Repeated measures ANOVA				x	x
Kruskal-Wallis H test (dependent)					x
Friedman (independent)					x
Tukey's post hoc test					x
Pearson's correlation coefficients	x				
Spearman's rank-order correlation		x			x
Cohen's d effect size				x	

3.6 ETHICAL CONSIDERATIONS

The studies included in the thesis were approved by The Regional Ethics board at Karolinska Institutet, Stockholm: Dnr 172/99 (Study I), Dnr 291/98 and 172/99 (Study II), Dnr 172/99 (Study III), and Dnr 2010/1023-31/1 with amendment 2012/509-32 (Studies IV and V).

The design of the voice accumulators used in these investigations guaranteed a preserved confidentiality for the participant wearing the device as well as for persons with whom the participant communicated. When the DAT recorder was used, it was possible to listen to the recorded sound-file. This was done by the research administrator only, to assure good recording quality. Data were de-identified and stored in a manner that ensured anonymity and confidentiality.

4 RESULTS

4.1 STUDY I

The aim was to evaluate the VAC's two software under laboratory condition, and to test the VAC in field recordings. The correlation between the VAC's two software and the Soundswell program was high ($r \geq 0.85$) for all participants but one. A prerequisite for reliable vocal fold vibration detection by the VAC was a careful placement and a firm attachment of the contact microphone on the neck. Results from the field condition showed that the VAC was an overall reliable instrument for long-term measurements of f_o and phonation time. A female speech-language pathologist who was teaching students had the highest value for phonation time at work, 27%, and a male research engineer, working silently in technical activities, the lowest at 3%. No consistent trends (i.e. an increase or decrease) of f_o were found among the participants during the workday.

4.2 STUDY II

In this study, the VAC was evaluated against a binaural DAT method. The results showed good agreement between the two methods in reference to f_o and phonation time. The two methods measured f_o equally well for normal, breathy and strained voice quality. The VAC gave a somewhat lower f_o value for creaky voice quality in comparison to the DAT recording, -3.2% or -0.56 semitones (ST). In general, the VAC registered somewhat lower values of phonation time as compared to the DAT for breathy, strained, and normal voice. The difference was larger for creaky voice quality; an 8.9% lower value for the VAC in comparison with the DAT. The VAC failed to register high frequencies above around 440 Hz as well as lower intensities. Three women working at daycare centres were recorded with the VAC and the DAT simultaneously during a workday. High correlations ($r_s \geq 0.80$) between the two methods' measurements of f_o and phonation time were found for two of the participants. For one participant with a higher level of subcutaneous soft tissue on the neck, the registration with the contact microphone was not reliable.

4.3 STUDY III

The aim of the study was to collect data on f_o and phonation time using the VAC with vocally healthy preschool teachers ($N = 12$). Results from two days of recordings showed that mean f_o was relatively high during the workday (266 Hz) and decreased significantly after work (to 246 Hz) ($P < 0.001$). The preschool teachers had few opportunities for voice rest. Phonation time during work varied largely among the participants with an average of 12.0% and decreased significantly after work during leisure time to 5.5% ($P < 0.001$). The participants estimated their voice use during the workday as being 75.5% of the total work time. Group mean values for f_o and phonation time did not vary to any large extent between day one and day two. However, two participants showed large individual differences between the days. No consistent trends (increase/decrease) of f_o were found among the participants during the workday. Individual variation in f_o across and between the workdays was large and dependent on speaking activity.

4.4 STUDY IV

Based on average measures for L_{eqV}, f_o and phonation ratio, there were no significant differences between the patients and their matched controls. There were, however, significant differences between the patients with phonasthenia and the patients with vocal nodules, as well as between the controls to the patients with phonasthenia and the controls to the patients with vocal nodules. Average environmental noise level was significantly higher during the work condition for patients with vocal nodules (73.9 dBA) and their controls (73.0 dBA) compared to patients with phonastenia (68.3 dBA) and their controls (67.1 dBA). Average voice level and f_o were also significantly higher during the work condition for patients with vocal nodules and their controls compared to patients with phonastenia and their controls. L_{eqV} and f_o increased with higher noise levels. The patients with vocal nodules and their controls decreased their mean f_o during leisure, as compared to the work condition, whereas the patients with phonasthenia increased their mean f_o during leisure. The average phonation ratio was significantly higher during the work condition for the patients with vocal nodules (18.2%) compared to the patients with phonasthenia (13.6%). During leisure time, there were no significant differences in average noise, voice level, f_o nor phonation time between the patient groups. The patients with vocal nodules and their controls spent significantly more time, and used their voices to a significantly greater extent, in high environmental noise levels.

4.5 STUDY V

Averages of the subjective ratings and instrumental measures did not differ significantly between the five working days or between the two work-free days. The patients rated vocal fatigue and hoarseness to a significantly higher degree compared to the vocally healthy controls ($P < 0.001$), as expected. There was a strong correlation between the two voice symptoms. The average ratings increased during the workday, and the level remained high in the evening. Only vocal fatigue decreased significantly for the patients with vocal nodules during the two work-free days. Subjective ratings and instrumental measures had similar patterns during the week. All participants had significantly higher levels of phonation ratio during workdays compared to work-free days ($P < 0.001$). A majority of the participants (32 of 40) showed a significant correlation between self-rated speaking time and phonation ratio. The patients with vocal nodules and their controls rated levels of disturbing noise ($P < 0.05$) significantly higher compared to the patients with phonasthenia and their controls during workdays, which was in agreement with instrumental measures of environmental noise levels.

5 DISCUSSION

5.1 METHODOLOGICAL ISSUES

5.1.1 Portable methods for long-term voice registration

The overall aim of this thesis was to evaluate methods based on portable devices for long-term voice registrations, and to assess voice use at work in women with vocally-demanding professions. The first question to address was, how can voice use in daily life be measured in a valid, reliable and practical way? The portable methods used in the studies proved to be useful instruments for long-time measurements of voice use, despite their limitations. The two voice accumulators VACLF1 (VAC) and VoxLog, and the binaural DAT method, each had their own advantages and disadvantages. The balance between measurement accuracy and the need for practicality and convenience needs to be considered when choosing an instrument. For example, the two voice accumulators had different types of microphones and sensors. Thus, if there is a choice, is a contact microphone preferable because it is small and discrete, and can be firmly attached with adhesive tape to the front of the neck of the participants, but which carries with it the risk of annoyance from skin irritation? Or is a neck collar with a microphone and accelerometer attached to it preferred as it is easy to slip on and off, but which has a risk of a loose fit on the neck and displacement during long-term measurements? A limitation with the VAC and the contact microphone, was that only f_o and phonation time could be measured and not SPL. Excessive values of voice SPL are believed to be a risk factor for functional voice disorders (Cantor Cutiva et al., 2013; Vilkman, 2004). Therefore, the VoxLog and the collar with an accelerometer and an airborne microphone was an important step forward in the project since it allowed for measurements of the speaker's voice SPL as well of the environmental noise.

Furthermore, ethical considerations with confidentiality when conducting audio recordings need to be balanced against the fact that the validity of the f_o extraction cannot be verified by inspection when using the voice accumulators, since the audio signal is not recorded and voice data are stored as averages within set time frames. With the voice accumulators, the integrity for the user was ensured because the sound was not recorded and, therefore, it was not possible to interpret the semantic content of the speech signal. On the other hand, the advantage with the binaural DAT method was that, since the audio signal was recorded, it was possible to scrutinize the signal and the analyses to diagnose technical problems, such as failed f_o extraction. However, it was of ethical concern that the confidentiality for the participants wearing the device, as well as for persons with whom the participants communicated, was not strictly kept in Study II, since it was technically possible to listen to the recorded DAT sound files. Only the research administrator had access to the sound files and listened to only parts of the recordings in order to assure that the recordings, and the resulting analyses, were of good quality. The participants had given their informed consent prior to data collection and data were de-identified and stored in a manner that ensured anonymity. Another disadvantage of the DAT method was the slow handling incurred by having to play back the recordings in real time. With modern solid-state recorders, this would not be a great concern.

The reliability of the VAC's detection of vocal fold vibration depended on accurate placement and firm attachment of the contact microphone to the participant's neck. For example, the detection was negatively influenced by factors such as a beard, subcutaneous soft tissue or loose skin. It would have been advantageous with a portable oscilloscope for use in the field condition to permit checks of the contact microphone signal before and during recording, in order to ensure a good quality vocal fold vibration signal. A disadvantage of the contact microphone was skin irritation from the adhesive tape, which was reported by one third of the participants in Study III. Hunter (2012) described that participants who carried a voice dosimeter for two weeks also experienced skin irritation because of the adhesive tape. An advantage of the contact microphone was that, once placed and well attached to the neck, it did not risk being displaced. Practical advantages with the VoxLog's neck collar, on the other hand, were that the collar was comfortable to wear and easy to put on and take off. Besides, since the microphone was calibrated for SPL by the manufacturer (Sonvox AB) no further calibration during the recordings was needed. However, thorough instruction by the research administrator to the participants regarding how to place the neck collar was required in Studies IV and V. A disadvantage of the collar was that it could move out of position during long-term recordings, if the participant was not vigilant as to its placement. This could compromise measurement stability. Possible artefacts due to a displaced collar were not possible to detect during data analysis, unless obvious erroneous parts of the recordings were visible during inspection of the data graphs. For example, in one case, data from part of one day's recording were manually excluded before analysis was performed because data were visibly inaccurate, caused by a loose microphone cord. The first model of the VoxLog collar tended to be too large for thin necks. To ensure firm placement of the collar onto the neck, the gap between the collar and the neck was, therefore, filled with a small pad that was placed at the back of the neck if needed. This problem was partially remedied when the adjustable collar became available. The second model was more robust and adjustable: it had the accelerometer and microphone attached to the same end, which was an advantage to ensure a more stable placement of the detectors. Still, an even smaller collar is needed in future studies using the VoxLog, especially if children are to participate.

The VAC's two software both had strengths and weaknesses. The advantage of VACF0, optimized for f_o measurements, was that it was less sensitive to disturbances, since periods that differed more than 25% in frequency from the proceeding period were sorted out. On the other hand, this risked causing an underestimation of phonation time. The advantage of VACPT, optimized for measurements of phonation time, was less risk of underestimation of phonation because all periods were accepted in the f_o range of 60 to 400 Hz. However, the VACF0 program was chosen in Study III since the participants were preschool teachers who could be expected to occasionally use an f_o exceeding 400 Hz.

The accuracy with which the voice accumulators registered f_o was likely to vary because of differences in voice quality. For example, hoarseness, rough voice and vocal fry are characterized by perturbations, i.e. irregularities in amplitude and frequency of the voice pulses from period to period (Askenfelt & Hammarberg, 1986). Results from Study II showed that the

VAC's measurement accuracy decreased in "creaky" voice quality. The presence of perturbations, irregular periods, are well-known challenges for f_o extraction (Hammarberg, 1986; Titze, 1995; Titze & Liang, 1993), however has hardly been addressed in studies using voice accumulators or voice dosimeters. Patients with work-related voice disorders are likely to be more or less dysphonic, with the presence of irregular vocal fold vibration patterns, which may influence measurement accuracy. Titze (1995) classified three types of voice signal. Type 1 signals are very close to being periodic. Type 2 signals contain irregular period alternations and strong subharmonics with energy levels approaching the energy of the f_o. Therefore, no obvious single f_o but several candidates can be present, which creates problems for f_o extraction methods. Type 3 signals have no apparent periodic pattern at all. Normal voices can be classified as type 1, or sometimes type 2, whereas voice disorders can lead to all three types of signal (Little, McSharry, Roberts, Costello, & Moroz, 2007). Consequently, f_o analysis is unequivocal only for type 1 signals, and not for type 2 and 3 signals (Little et al., 2007). Since the voices of patients with work-related voice disorders may be breathy, rough or creaky it is important to investigate how reliable voice accumulators and voice dosimeters are in the estimation of f_o, voice SPL and phonation time for different voice qualities, including irregular phonation patterns and turbulent noise.

Neither of the two voice accumulators was perceived by the participants in Studies III-V as having any objectionable influence on work or leisure activities. However, participants in previous studies with ambulatory voice monitors have reported that they were disturbed by wearing the NCVS equipment (Hunter, 2012). User acceptability is likely to increase with smaller and lightweight equipment, and this is something that is taken into account in the technical development of ambulatory voice monitors using, for example, smartphones (Mehta, Zanartu, Feng, Cheyne, & Hillman, 2012). Wireless devices would also be a step forward in the development to increase user friendliness.

Both the VAC and the VoxLog were equipped with a light emitting diode (LED) that signaled when phonation was being registered. The participants were instructed to check the LED on a regular basis to verify ongoing voice registration and to let the researcher know immediately if the device was not working properly. Lengthy data collection periods require that the researcher travel to meet with the participants regularly to verify the equipment function, give technical support if needed, and to ensure the participants' compliance with the study protocol (Nix et al., 2007). Whenever possible, data was downloaded by the researcher during the week of the recording, in order to verify the data and to change the equipment if needed. For example, this procedure allowed detecting and replacing of the faulty microphone cord for one of the participants in a timely manner.

Data from the VAC and the VoxLog were transferred with the two devices' software to a spreadsheet program, where analysis were performed. In addition to f_o, phonation time and SPL of the voice and environmental noise, VoxLog also computes the "cycle dose". This dose measure is based on f_o and phonation time and indicates the total number of vocal fold oscillations during the measurement period. The dose measure was not included in Studies IV and V since the aim was to examine variations of each parameter separately, for example to see how the parameters were affected by environmental noise, and how each parameter affected subjective ratings, e.g., vocal fatigue. Compared to the relatively easy analysis procedure for the voice accumulator data, the process of acquiring and analyzing the speech sound signal recorded with the binaural DAT method was more time consuming and required considerable technical expertise.

5.1.2 Subjective ratings

A methodological advantage with subjective ratings, compared to long-term voice accumulation, is that they are user-friendly for both the participant and the researcher (Carding et al., 2009). Nevertheless, some participants in Study V perceived it as tiring to fill in the repetitive series of ratings of voice use and voice symptoms four times a day over a week. One participant filled in the midday ratings retroactively a couple of times due to dense and stressful workdays. Furthermore, it is possible that the vocally healthy controls filled in the rating sheets without too much reflection, since they in most cases experienced little or no symptoms, which may have had an impact on the rating scores. However, a strength in Study V was that the response rate for the subjective ratings was very high. Instead of conducting the ratings on paper, which was the case in Studies III and V, time-stamped electronic ratings preceded by push notifications would be a methodological advantage in future studies.

5.1.3 Participants

In Studies I and II, employees at Karolinska Institutet, Stockholm, volunteered as participants. Convenience sampling was used since only a small number of participants were required for the evaluation of the VAC, with the inclusion criteria that the participants were vocally healthy. Only female participants were included in Studies III-V since work-related voice disorders are more common in women (Fritzell, 1996; Hunter et al., 2011; Roy et al., 2005), and to facilitate comparison of group data. The number of participants in the field Studies III-V were limited and was not based on power analysis due to the exploratory set up of the studies. The participants in Studies IV and V were the same. The initial target was 60 participants; 30 patients and 30 vocally healthy controls. After 53 recruited participants, whereof 13 dropped out, the recruitment was terminated due to financial and time constraints and landed at 40 participants. However, a relatively small number of participants is common in field studies using portable voice monitors, as can be seen in Tables 1 and 2 in the introduction section of this thesis report. Even though larger study populations are warranted, this requires careful planning and financial and administrative resources, since recruitment and data collection are cumbersome (Nix et al., 2007). Participation in Studies IV and V required compliance to the study protocol during the week of data collection, including checking the VoxLog and filling in the self-ratings. Furthermore, the participants had to travel to the voice clinic to take part in an about 1½-2 hours procedure including videolaryngoscopy, voice recording, filling in questionnaires and an interview. It is possible that there was a selection bias excluding participants with time and logistical constraints in favour of participants that were really interested and committed to participation. It was especially difficult to recruit the vocally healthy controls that had less personal motivation to participate due to lack of voice problems. The controls were remunerated with two movie tickets each for their participation. Field studies with larger participant groups have been conducted in the US where it has been possible to give financial compensation to the participants (e.g. Hunter & Titze, 2010; Van Stan et al., 2015). A methodological strength with Studies IV and V was that the patient and control persons were well matched for workplace, and that a large amount of data was collected per participant. Yet, the findings should be seen as explorative and not be generalized without caution, due to the limited number of participants in each patient group. Because multiple statistical analyses were conducted on the small group samples, there was a risk of a type 1 error, i.e., the detection of an effect that is not present.

5.1.4 Measurement time

Individual variation in voice use and voice symptoms from day to day, in combination with the small group size, could confound the overall parameter averages in Studies IV and V. However, since no significant differences in average subjective ratings or instrumental measures were found in Study V between the 5 workdays, nor between the 2 work-free days, this confounding risk seems minor. It is possible that a period of data collection shorter than a week could have been favorable for the participant recruitment, e.g. 2 workdays and 2 workfree days. However, since other studies have reported variation in voice symptoms during a workweek and weekends (Sala et al., 2001; Smolander & Huttunen, 2006), data from a whole week including workdays and workfree days was deemed preferable. Mehta et al. (2012) addressed the question of how long measurements should be to provide accurate and reliable results. This is relevant considering the cost and inconvenience associated with long-term voice accumulation (Mehta et al., 2012; Nix et al., 2007). Mehta et al. (2012) estimated that at least accumulated 26 hours is needed for optimal monitoring of f_o, phonation ratio and SPL to yield errors below 10%.

5.2 VOICE USE AT WORK IN WOMEN WITH VOCALLY-DEMANDING PROFESSIONS

5.2.1 Patients vs. vocally healthy controls

The second major question that was addressed in this thesis was if voice use differs between vocally healthy individuals from those diagnosed with a work-related voice disorder. Studies IV and V are among the first field studies to include patients with occupational voice disorders using long-term voice accumulation to study variation in voice use in relation to environmental noise. The results were partly unexpected. It was anticipated that the patients either would speak more and louder compared with the vocally healthy controls or speak less, to rest or conserve their voices, because of the voice disorder. Neither scenario proved to be true. Long-term averages of phonation time, f_o and voice SPL did not provide a basis for differentiating voice use between patients and vocally healthy controls, when the patients were grouped together. Similar results were reported by Van Stan et al. (2015) who did not find any significant differences between patients with vocal nodules or polyps and matched controls (although not matched from the same workplace) regarding average measures of phonation time, cycle dose, distance dose, f_o and voice SPL, based on weeklong recordings with a smartphone-based voice dosimeter. However, when the present data were analyzed separately for the patients with phonasthenia and their controls and for the patients with vocal nodules and their controls, significant differences were found regarding both instrumental and subjective measures (Studies IV and V). The patients with vocal nodules and their controls were exposed to significantly higher levels of environmental noise, spoke significantly more and louder at work, and used higher f_o than the patients with phonasthenia and their controls. The patients with vocal nodules and their controls also rated significantly higher levels of disturbing noise. These findings imply that high environmental noise levels in the work environment and demands from the occupation have a greater impact on vocal behaviour than do individual factors. A lesson learnt was that, as patients with work-related voice disorders are not homogenous, it is important to differentiate between patient groups when assessing voice use in field studies. The division of the patients into subgroups led to fewer participants per group for statistical comparisons than planned.

No significant difference regarding average instrumental measures differentiated the patients from the vocally healthy controls. This does not mean that they reacted in the same way to the vocal loading. Vocal loading often manifests as an increase in subjective symptoms (Whitling et al., 2017; Vilkman, 2004). As expected, findings from Study V showed that the patients rated vocal fatigue and hoarseness to a significantly higher degree compared to the vocally healthy controls. The average ratings increased during the workday and remained high in the evening, a finding that is in agreement with increased vocal fatigue and hoarseness over a workday in customer call centre workers (Lehto et al., 2006, 2008). However, it seems that the patients in Study V did not differentiate between the two voice symptoms to any large extent, since there was strong correlation between rated vocal fatigue and hoarseness. It is possible that the instructions to the participants were not clear enough for them to be able to discriminate between the two symptoms.

5.2.2 Work condition vs. leisure condition

In order to determine whether or not voice problems are related to vocal strain at work, it is essential to measure voice use both at work and outside the workplace during leisure time. Results from Study III showed that preschool teachers used higher average f_o and phonation time during work as compared to leisure time, indicating high vocal load caused by the activities at work. Results from Study IV confirmed the finding in Study III, that phonation time was higher during work than leisure for both patients and controls, but the results were not in congruence regarding f_o. In Study IV, no significant differences were found between work and leisure conditions with regard to average measures for f_o and levels of the voice and environmental noise. Titze and Hunter (2015) reported f_o and phonation time findings in agreement with Study III. In their study (Titze & Hunter, 2015), teachers were monitored for 2 weeks with the NSCV voice dosimeter. Total cycle dose, which accounts for both f_o and phonation time, in the work condition was approximately 2.0 million cycles for female teachers in an 8-hour teaching day. The cycle dose in the leisure condition was about half that amount (Titze & Hunter, 2015). Furthermore, the female teachers showed significantly higher average f_o at work compared to outside work hours (i.e. morning, evenings and weekends). This was also the case for the patients with vocal nodules and their controls in Study IV, who decreased their mean f_o during leisure, as compared to the work condition. In contrast, the patients with phonasthenia increased their mean f_o during leisure time. Furthermore, in the study by Titze and Hunter (2015) female teachers showed significantly lower average voice SPL during leisure time. Contrasting findings were found in Study IV. The patients with phonasthenia and their controls increased voice SPL significantly during leisure time as compared to the work condition, whereas no significant difference for the patients with vocal nodules and their controls was found between the work and leisure conditions. Based on these results, it is not possible to conclude whether an increase or decrease in average f_o, during and after a workday, reflects adequate adaptation to vocal loading and noise, or if it is a sign of vocal fatigue, and thus constitutes a risk to vocal health (Laukkanen et al., 2008; Lehto et al., 2008; Rantala et al., 2002). However, it was confirmed that voice level and f_o increased with higher noise levels, as expected.

Note that there was a methodological difference between Studies IV and V. In Study IV, differences were investigated between work and leisure conditions. Included in the work condition were the first and second halves of the workdays, and included in the leisure condition were the mornings, evenings and workfree days. In Study V, differences were investigated between workdays and workfree days. Included in the workdays were also the mornings and evenings. This difference in categorization had implications for the results. In Study V, no significant difference in average noise SPL between workdays and workfree days was found. However, when results from the daily time intervals were compared in Study V, a pattern emerged where average noise SPL was significantly higher during work time for the patients with vocal nodules and their controls, compared to the patients with phonasthenia and their controls, a finding congruent with noise SPL results from Study IV.

5.2.3 Environmental noise

To avoid the speaker having to increase voice SPL, and to maintain speech intelligibility, conversation should be limited to being in noise levels that do not exceed 55 dBA (Yiu & Yip, 2016). The average environmental noise levels at work in Study IV ranged from 68.3 to 73.9 dBA. Such high noise levels are clearly detrimental to speech communication and may have negative consequences both for the speaker and for the listener. To be heard at 1 m in noise levels of 70 dBA, the speaker has to increase voice SPL to some degree. With a greater speaking distance, or at noise levels around 80 dBA, the speaker needs to shout (Arlinger, 1999; The Swedish Work Environment Authority's provisions for noise, AFS 2005:16). Self-to-other ratio (SOR) was calculated as the difference between the voice level and the environmental noise level. The patients with vocal nodules had a significantly higher SOR than the patients with phonasthenia during the work condition. An interesting finding was that the patients with vocal nodules, furthermore, had a significantly higher SOR compared to their controls. This can be interpreted to mean that the patients with vocal nodules used higher voice SPL than necessary to make themselves heard in noise. Voice amplification has proved to be an effective (and low-cost) intervention for individuals with vocally-demanding professions, such as teachers, to decrease SOR and potentially prevent vocal overload (Bovo, Trevisi, Emanuelli, & Martini, 2013; Gaskill, O'Brien, & Tinter, 2012; Jonsdottir, Laukkanen, & Siikki, 2003; Morrow & Connor, 2011b; Roy et al., 2002; Sapienza, Crandell, & Curtis, 1999).

5.2.4 Estimated speaking time vs. phonation time

In Study III, the 12 vocally healthy preschool teachers rated on a VAS their estimated amount of voice use during a workday as 76%. The vocally healthy controls in Study V rated on a VAS a considerably lower average estimated speaking time for workdays of 44%. This difference may be due to a change in terminology and how the question was asked between the studies. In Study III the participants were asked "How much do you think you use your voice during a day?" The end points of the VAS stated 0% and 100%. They were asked to complete the VAS by the end of the first workday. In Study IV the participants were asked to fill in the VAS four times per day: "This morning (or before lunch, afternoon, evening) I have spoken…" The end points of the VAS stated "Not at all" "A lot". In Study V, the average value for estimated speaking time was based on 4 ratings from 5 workdays, including mornings and evenings.

In contrast to phonation time, which includes only voiced segments, speaking time also contains voiceless speech sounds and pauses. Mehta et al. (2016) reported that patients with vocal nodules and polyps and vocally healthy controls overestimated their speaking time in relation to the phonation ratio. In line with the same principle as in the study by Metha et al. (2016) that the ratio between estimated speaking time (rated on a 100 mm VAS) and phonation ratio (%) is approximately of 2:1, the patients and vocally healthy controls in Study V also overestimated their speaking time. Nevertheless, despite a certain overestimation of speaking time, which in itself is understandable, the rated speaking time followed a pattern over time similar to that of the measured phonation ratio. Thus, the participants seemed to have a relatively good perception of the variations of how much they talked at different times of the day. In Study V, correlations between estimated speaking time and phonation ratio measured with the VoxLog were calculated at individual level and not at group level. Thirty-two of 40 participants showed a significant correlation between self-rated speaking time and phonation ratio. In a study by Misono, Banks, Gaillard, Goding, and Yueh (2015) vocally healthy participant were recorded with the VocaLog, and during the recording, they rated their speaking time every 15 minutes over a 2-hour period. The results showed a moderate correlation (r = 0.62) at group level between self-reported speaking time and phonation ratio (Misono et al., 2015).

Since the validity and reliability of self-ratings by patients with work-related voice disorders and occupational voice users have been questioned (Bastian et al., 1990; Karnell et al., 2007; Mehta, Van Stan, & Hillman, 2016), the findings in Study V were a bit unexpected. It seems that patients and vocally healthy controls from the same workplace, who are asked to reflect on their voice use and symptoms and rate those several times a day, could give a rather accurate picture of the variation in how much time they spent talking, as well as of the amount of disturbing environmental noise, that matched the instrumental measurements. Similar results were reported in a recent study by Schiller, Morsomme, and Remacle (2017). In that study, music teachers' voice use was registered with the VoxLog, at the same time as subjective self-ratings were collected. The results showed that the music teachers seemed to have a good awareness of how much they used their voices and the influence of voice use on vocal fatigue and voice quality (Schiller et al., 2017). These are encouraging findings, since reliable patient reports of the amount of voice use and environmental noise are useful for understanding the origin of occupational voice disorders (Vilkman, 2004).

5.2.5 Correlations between vocal fatigue and acoustic measurements

To know how patients with voice disorders perceive their voice use, and how voice symptoms correspond to instrumental measurements is of both theoretical and clinical interest. However, examined relationships between vocal fatigue and acoustic measurements have not been conclusive in previous studies (Buekers, 1998; Laukkanen et al., 2008; Laukkanen et al., 2004; Rantala & Vilkman, 1999). In Study V, correlations between vocal fatigue and phonation ratio, and correlations between vocal fatigue and voice SPL, did not exhibit any clear differences between the participant groups, apart from that more patients with phonasthenia (5 of 10) showed a significant correlation between vocal fatigue and phonation ratio compared to the patients with vocal nodules (1 of 10). This would be consistent with the assumption that patients with phonasthenia are more sensitive to vocal fatigue and to how much they use their voices. The variability between participants regarding significant correlations suggests that some individuals may be more aware and consistent in their self-assessment of voice use than others, a fact that was noted also in the study by Misono et al. (2015).

5.3 MULTIFACETED DATA COLLECTION AND INDIVIDUAL FACTORS

Since vocal behaviour is a complex phenomenon a multifaceted research approach is needed to cover different risk factors for occupational voice disorders (see Table 3 in the introduction section of the thesis). In addition to the subjective and instrumental measures included in Studies IV and V, it would be interesting in future studies to apply a mixed method approach, including also qualitative data that addresses participants' experiences and perceptions about their voice use and vocal health in greater depth. The relationships between voice use and vocal health and stress, anxiety, psychosocial factors, personality traits, lifestyle, awareness, coping strategies and self-management have been addressed but need further attention (Dietrich et al., 2008; Holmqvist et al., 2013; McHugh-Munier, Scherer, Lehmann, & Scherer, 1997; Ng et al., 2013; Oliveira et al., 2012; Van Wijck-Warnaar et al., 2010; Yano, Ichimura, Hoshino, & Nozue, 1982). For example, extroversion, hyperactivity, impulsiveness and perceived stress are traits found in patients with vocal nodules (El Uali Abeida et al., 2013; Roy, Bless, & Heisey, 2000). The connection between stress and vocal nodules needs further investigation since chronic stress has an immunosuppressive effect, which could negatively influence wound healing in phonotraumatic lesions (Holmqvist Jämsén, 2017).

Another important aspect that needs further attention is the fact that a general lack of awareness of vocal health risks increase an occupational voice user's vulnerability to voice disorders (de Jong et al., 2003; de Jong et al., 2006). Individuals with vocally-demanding and noisy work environments should be encouraged to pay attention to and be aware of voice symptoms as being early signs of voice problems, since adequate treatment of early symptoms is important (Solomon, 2008; Vilkman, 2000, 2004). Individuals suffering from work-related voice problems often hesitate to seek medical care for their voice problems (Da Costa, Prada, Roberts, & Cohen, 2012), with the possible consequence that minor voice issues escalate due to the lack of timely diagnosis and treatment. Reacting to heavy vocal loading is an essential coping skill for individuals with vocally-demanding professions (Whitling et al., 2017). Since patients with functional voice disorders are extra vulnerable to heavy vocal loading, Whitling (2016) stresses the need for these patients to learn coping skills for how to avoid overload when speaking in noise.

A new generation of methods for long-term accumulation of vocal behaviour based on smartphone platforms is on the way (Mehta et al., 2012). The questions triggering new technical development are if we are measuring the right thing in the right way? For example, phonotraumatic lesions, such as vocal nodules, are not only associated with high voice SPL, but also hyperfunctional voice use (Hillman et al., 1990; Titze & Hunter, 2015). In a pilot study, Ghassemi et al. (2014) tested an accelerometer-based ambulatory monitoring tool to be used to identify and differentiate patterns of voice use that are associated with hyperfunctional voice disorders. Machine learning was applied to distinguish between patients with vocal nodules and vocally healthy controls using SPL and f_o data derived from an accelerometer (Ghassemi et al., 2014). Novel real-time estimation of aerodynamic features estimated from the accelerometer signal has also been tested for ambulatory voice monitoring (Fryd, Van Stan, Hillman, & Mehta, 2016; Llico et al., 2015). Furthermore, a method including Cepstral Peak Prominence Smoothed was recently tested on vowels extracted from text readings in order to differentiate between dysphonic speakers and vocally healthy speakers (Castellana, Selamtzis, Salvi, Carullo, & Astolfi, 2017). The intention is to apply this automatic method to long-term monitoring of voice use in daily life (Castellana et al., 2017).

6 CONCLUSIONS AND IMPLICATIONS

Even though the voice accumulator VACLF1's measurement accuracy decreased at low voice levels and at high f_o, it proved overall to be an effective instrument for long-term measurements of f_o and phonation time (Studies I-III). A limitation of the method was that it did not allow for recordings of voice SPL. A more recent voice monitor, VoxLog, was therefore used in Studies IV and V, since it allowed for SPL measurement of the voice, as well as of the environmental noise.

A disadvantage of the DAT method was the slow handling incurred by having to play back the audio recordings in real time. However, with modern solid-state recorders, this would be of little concern nowadays. Ethical considerations with confidentiality when conducting audio recordings with the DAT method need to be balanced against the fact that the validity of the f_o extraction can be verified by inspection, which is not possible when using the voice accumulators.

A prerequisite for reliable vocal fold vibration detection with the voice accumulator was that the contact microphone was carefully placed and firmly attached to the neck. Subcutaneous soft tissue on the neck caused problems, which implies that the physical condition of the user's neck needs to be considered before initiating recordings (Studies I and II).

Analysis of weeklong recordings of voice use and environmental noise, in females with vocally-demanding professions, showed no significant differences in average measurements of L_{eqV}, f_o, and phonation ratio between patients with work-related voice disorders and vocally healthy controls (Study IV).

Significant differences in average measurements of L_{eqV}, f_o, and phonation ratio between the patients with phonasthenia and vocal nodules imply that patients with work-related voice disorders are heterogeneous (Study IV). The patients' medical diagnosis should be considered when studying vocal behaviour in patients with work-related voice disorders.

The patients with vocal nodules and their controls were exposed to significantly higher levels of environmental noise, spoke more and louder, and used higher f_o than the patients with phonasthenia and their controls, in the work condition. The findings suggest that high-environmental noise levels in the workplace, and demands from the job, have a greater impact on vocal behaviour than do individual factors (Study IV).

Furthermore, findings from field recordings with the VAC and VoxLog indicate high vocal load caused by work demands among preschool teachers (Study III), and females with vocally-demanding professions including for example preschool teachers, teachers, nurses and phone operators (Studies IV and V), since phonation ratio was significantly higher in the work condition than in the leisure condition.

Both the patients with phonasthenia and those with vocal nodules showed a strong correlation between perceived vocal fatigue and hoarseness, which indicates that they did not differentiate between the two voice symptoms to any large extent. Average ratings of vocal fatigue and hoarseness increased during the workday and remained high in the evening (Study V) implying that it takes time to recover from vocal loading.

Vocal demands and environmental noise levels were reflected in both subjective ratings and instrumental measurements. Data for a majority of the participants showed significant correlations between self-rated speaking time and phonation ratio. The patients with vocal nodules and their controls rated levels of disturbing noise significantly higher compared to the patients with phonasthenia and their controls during workdays, which was in agreement with instrumental measures of environmental noise levels. The subjective ratings and instrumental measurements exhibited similar patterns over a week, which implies that the patients and vocally healthy controls, matched from the same workplace, appeared to have a reliable perception of how much time they spend talking, and of the levels of disturbing environmental noise (Study V). The results indicate that patient self-reports of voice use, disturbing environmental noise, and voice symptoms are useful to collect, if this is done in a structured way.

Individuals with vocally-demanding and noisy work environments should be encouraged to pay attention to voice symptoms as being early signs of voice problems, in order to avoid developing a voice disorder that requires medical voice care.

The finding that the patients with vocal nodules and their controls were exposed to significantly higher levels of environmental noise strongly emphasizes the need for interventions to reduce environmental noise levels. This would aim to improve voice ergonomic conditions and preserve vocal health for individuals working in communication-intensive and vocally-demanding workplaces.

To facilitate voice rehabilitation and to prevent work-related voice disorders, employers and occupational health representatives need to be educated about how to include assessment of voice ergonomic factors as part of their systematic work environment management.

7 FUTURE DIRECTIONS

During the time period of the thesis work, research has shown that it is difficult to define safe limits for occupational voice use, due to large individual variations in response to vocal loading (Dejonckere, 2001; Manfredi & Dejonckere, 2016; Titze & Hunter, 2015; Vilkman, 2004). Therefore, a prerequisite for progress in the field of voice ergonomics is the continued development of valid and reliable methods to study voice use and voice symptoms in daily life, so as to identify risk factors to vocal health.

The next step is to translate research evidence into clinical practice and implementation of voice ergonomic measures in vocally-demanding and/or noisy work environments. For this purpose, the development of convenient tools for risk assessment of work-related voice disorders is of fundamental importance.

Studies are called for that embrace a health economic perspective on workplace voice use and prevention of voice disorders. Discussions with employers would benefit from knowledge about the cost for implementation of measures in the workplace, such as voice amplification and acoustic treatment of rooms, in relation to financial gain from avoided productivity loss, in terms of costs for sick leave and staff turnover.

A standardized instrument for measurement of voice symptoms is needed, to facilitate comparisons between studies. It is also important that the vocabulary describing the voice symptoms is validated with lay-persons as subjects.

Longitudinal studies are needed to shed light on why some individuals develop voice disorders, while others do not. We do not know why the patients in our studies had developed voice disorder, and the controls had not, despite the similar working conditions and vocal demands. A longitudinal study including detailed information about individual factors could reveal if the controls may also be at risk of developing voice disorders.

It would be interesting in future studies to explore variations in f_o and voice SPL in relation to vocal loading and environmental noise in more detail for individual participants. Intervention studies could include customized voice education, teaching individual strategies for speaking in environmental noise based on the individual’s vocal capacity and limitations.

The difficulties with f_o extraction for dysphonic voices have to be acknowledged. The reliability of voice accumulators and voice dosimeters in the estimation of f_o, phonation time and voice SPL for different voice qualities, including irregular vocal fold vibration patterns, and breathiness, needs further investigation.

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