Measuring listening effort in the field of audiology – a literature review of methods (part 2)

Messungen von Höranstrengung im Bereich der Audiologie – eine literaturgestützte Methodenübersicht (Teil 2)

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Abstract When studying the audiological literature it is evident that more and more attention is drawn to listening effort. The literature also shows that listening effort is an additional measuring dimension next to speech intelligibility describing comprehension of speech especially in noisy situations and should therefore be included in the evaluation of noisy listening conditions. The aim of this publication was to review the literature and to give an overview of the different methods employed to measure listening effort. Particular attention was paid to find a practical way to measure listening effort with a special focus on hearing aid evaluations. The keywords »listening effort«, »ease of listening«, »listening comfort« and »listening difficulty« were used in the search. 54 publications about listening effort were reviewed and analyzed according to type of measurement, focus of study, subjects and outcome. Three main types of listening effort measurement were identified: measurements of physiological reactions (especially pupillometry), measurements of cognitive performance, and subjective ratings (direct scaling of listening effort or questionnaires).

Key words Listening effort; listening difficulty; ease of listening; SNR; pupillometry; dual task paradigm

Zusammenfassung *Bei der Durchsicht der audiologischen Literatur wird deutlich, dass das Thema Höranstrengung zunehmend an Bedeutung gewinnt. Es zeigt sich, dass die Höranstrengung eine zusätzliche Messdimension beim Verstehen von Sprache mit Hintergrundrauschen darstellt und deswegen bei der Evaluation von Geräuschsituationen hinzugezogen werden sollte. Das Ziel dieser Publikation war, in einer Literaturrecherche die verschiedenen Methoden zur Messung der Höranstrengung zusammenzufassen. Ein besonderes Augenmerk war dabei die Suche nach einer praktikablen Methode zur Messung der Höranstrengung vor allem für die Evaluation von Hörgeräten. Die folgenden Schlagwörter wurden bei der Literatursuche benutzt: »listening effort«, »ease of listening«, »listening comfort« und »listening difficulty«. 54 Publikationen wurden im Hinblick auf Messtyp, Fokus der Studie, die Probanden und die Ergebnisqualität ausgewertet. Dabei wurden drei Haupttypen von Messungen identifiziert: Messungen der physiologischen Reaktionen (vor allem Pupillometrie), Messungen der kognitiven Leistungen sowie die Erfassung der subjektiven Bewertung der Höranstrengung (direkte Skalierung oder Fragebogenverfahren).*

Schlüsselwörter *Höranstrengung; Hörschwierigkeit; Signal-Rausch-Verhältnis; Pupillometrie*

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Main abbreviations in this review:
EXP=experiment
NH= normal hearing
HI= hearing impaired
SNR=signal-to-noise ratio
SRT= speech recognition threshold
fMRI = functional magnetic resonance imaging

Introduction (for part 2)

The goal of this literature review was to give an overview on the different methods to measure listening effort. The reviewed publications were divided into three main types of measurement methods: measurements of physiological reactions, measurements of cognitive performance and subjective ratings (direct scaling of listening effort or questionnaires). In part 1 of this review, 11 publications focusing on physiological reactions and 20 publications focusing on cognitive performance were discussed.

Most studies investigating physiological reactions used pupillometry as the method of choice. Also functional magnetic resonance imaging, electromyographic activity, skin conductance, skin temperature and heart rate were used to measure listening effort. Studies investigating changes in cognitive performance often focused on dual task paradigms, but also single-task paradigms and measures of working memory performance were used.

In the second part of this review, we will focus on studies using subjective ratings to measure listening effort.

Subjective ratings of listening effort

In addition to using indirect but objective measurements of physiological reactions or cognitive performance, listening effort can be also directly evaluated using questionnaires or rating scales. The results are based on the self-reported effort perceived by the subjects under different conditions. Self-reports included in this study focused both on ratings of listening effort but also on ratings of listening difficulty and ease of speech understanding.

There are several studies of physiological reactions or cognitive processing which also included subjective ratings of listening effort (please see part 1 of this review). In this section, experiments focusing especially on subjective ratings and scaling are presented.

Schulte and colleagues (2008) investigated the question whether listening effort and speech intelligibility were different factors to describe speech perception in noise or whether they influenced each other. Both, listening effort and listening difficulty were rated on a 60-point scale in 11 different SNR conditions. In experiment 1, NH and mildly and moderately HI subjects (using hearing aids) were presented with speech in either cafeteria noise or a stationary speech shaped noise (»olnoise«). Results showed that speech intelligibility increased and listening difficulty decreased with increasing SNR in both noise types. However, while intelligibility was greater in the »olnoise« condition over a wide range of SNRs, listening difficulty was rated lower in cafeteria noise (for similar result on listening effort see Schulte et al., 2007). Overall, the relationship between speech intelligibility and listening difficulty was not linear: Listening difficulty decreased relatively slowly for speech intelligibility conditions up to 98% intelligibility level, only showing a huge decrease in listening difficulty at conditions in which the intelligibility was approaching 100%. In experiment 2, the effects of noise reduction were investigated in HI subjects. Results showed that subjects perceived more effort during listening in olnoise when the digital noise reduction was switched off; when rating listening difficulty, the differences between both conditions were less prominent. Experiment 3 focused on the question whether long term spectra and/or modulation had an influence on the listening difficulty. Therefore, experiment 1 was repeated with NH subjects and the power spectra of the noise (cafeteria noise, olnoise, plus ICRA7 noise) were adapted to match each other. The ICRA7 noise was an artificial noise with a strong speech shaped modulation. The results were similar as in experiment 1, but speech intelligibility in ICRA7 noise was higher and listening difficulty was lower compared to olnoise and cafeteria noise at similar SNRs. For similar intelligibility levels, cafeteria noise was again rated as a less difficult condition than olnoise, and listening difficulty during the ICRA7 noise was perceived as being in between the other two noise types. Because of the differences in speech intelligibility and listening difficulty between the ICRA7 noise and the other two noise types the authors speculated that modulation might indeed be a factor influencing both effort and intelligibility but that it might not be the sole factor.

McAuliffe and colleagues (2012) investigated the effect of speaker age on speech intelligibility and perceived listening effort in older adults with hearing loss. They presented 19 elderly subjects with speech of low or high predictability which had been spoken either by young or by elderly subjects. They found that while the age of the speaker did not influence the intelligibility score it had a significant effect on the perceived listening effort: Elderly subjects rated the listening effort significantly higher when listening to the »aged« voice. The authors remarked that future studies would benefit from the inclusion of more challenging noise conditions and speech stimuli from very old speakers in order to improve communication exchanges between older adults.

Several studies investigated the influence of processing (e.g., compression algorithms, noise reduction algorithms and binaural processing) on listening effort. Humes and colleagues (1999) focused on the effects of two hearing aid compression algorithms on speech recognition and magnitude estimates of listening effort (MELE) of words and speech in quiet and babble noise in HI subjects. Speech performance in word and speech tests was found to be dependent on the listening condition and hearing aid use, showing significantly better performance with hearing aid use compared to unaided listening. Two-channel wide dynamic range compression (WDRC) provided significantly better results than linear compression in the speech test but did generally not influence the word test. Listening effort was rated significantly lower with hearing aid use, and the WDRC produced significantly lower effort ratings than linear compression in quiet conditions but did not show additional benefit in noise. Also a reduction of gain at low frequencies (BILL processing) did not affect speech tests or MELE rating compared to linear processing (Humes et al., 1997).

Marzinzik and Kollmeier (1999) investigated the influence of noise reduction algorithms on listening effort of NH and HI subjects in drill and cafeteria noise. The results showed that HI subjects perceived less effort in drill noise when two out of the four noise reduction algorithms were used; in the more fluctuating cafeteria noise, however, no beneficial effects of any algorithm were found. Speech intelligibility, on the other hand, showed no effects of processing for NH subjects while nearly all algorithms (except the E7 algorithm in drill noise) led to reduced intelligibility for HI subjects. These results suggest that noise reduction algorithms might be able to reduce listening effort – at least in stationary noise (see also Schulte et al., 2008) - but the algorithms tested here were not able to increase speech intelligibility and might, in contrast, have negative effects on speech intelligibility of HI subjects.

Luts and colleagues (2010) evaluated the influence of five noise reduction algorithms on speech intelligibility and listening effort for German and Dutch speech at four different testing sites. The researchers instructed subjects with NH, flat HI or sloping HI to perform speech intelligibility tests, paired comparison tests with preference rating and listening effort rating. During the tests all subjects (including the NH subjects) were using computer-controlled hearing aids while listening to processed or unprocessed speech in multi-talker babble in an office-like room with three noise sources. Additional intelligibility measurements in an office-like room with one noise source and in a reverberant room (RT>1s) with three noise sources were obtained in a subgroup of the subjects. Results showed that both speech intelligibility and listening effort depended on test site, hearing impairment and algorithm. The MWF algorithm always led to an increase in intelligibility, both in office-like rooms and in reverberant rooms. The BSS algorithm, on the other hand, lead to a decrease in intelligibility in both office-like rooms and reverberant rooms (except in office-like rooms with one noise source). Listening effort was generally reduced by the MWF algorithm and increased by the BSS algorithm in nearly all conditions (see also fig. 4). The algorithms SC1, SC2 and COH, on the other hand, affected the effort scores only at an SNR of 0 dB, offering a reduction of effort in this condition (for more details on the effect of SNR and algorithm on listening effort for NH and HI listeners see also Schulte et al., 2009). Preference ratings showed that the algorithms SC1, SC2, MWF and COH were preferred over the unprocessed condition while the unprocessed condition was preferred over the algorithm BSS. MWF led to the highest degree of preference while BSS had a negative preference score.

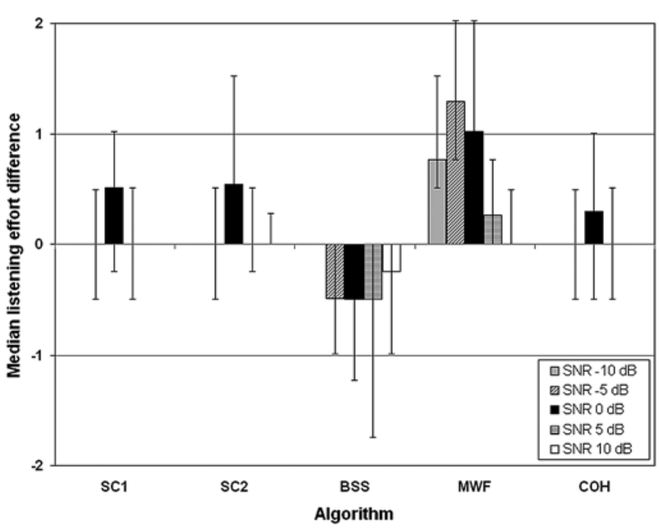

Fig. 4: Changes in perceived listening effort for speech in noise processed with different noise reduction algorithms in relation to the unprocessed condition. Error bars show the first and third quartiles (data taken from Luts et al., 2010).

Abb. 4: Änderungen der wahrgenommenen Höranstrengung für Sprache in Hintergrundgeräuschen durch verschiedene Störgeräuschalgorithmen im Vergleich zur unverarbeiteten Bedingung. Die Fehlerbalken geben die ersten und dritten Quartille wieder (Daten aus Luts et al., 2010).

Effects of noise reduction algorithms on (overall) ratings of comfort, ease of speech understanding and sound quality (but not intelligibility) of speech in quiet and noise were also found by Zakis and colleagues (2009). Mackersie and colleagues (2009) investigated the effects of different encoding strategies and amplifications (standard / individual) on subjective ratings of listening effort for speech in quiet and noise. No effects of encoding were found, but listening effort was rated significantly lower in quiet and when individual amplification was used.

Possible relationships between listening difficulty and different objective measures of room acoustics were investigated in several experiments by the group of Morimoto and Sato. In all experiments, listening difficulty was rated on a 4-point scale and then plotted as the percentage of difficulty responses (see Morimoto et al., 2004 for details); the speech signals were presented through a loudspeaker in an anechoic room using simulated sound fields which differed in several room acoustic parameters. Effects of early reflections and reverberations on listening difficulty of NH listeners were investigated by Sato, Bradley and Morimoto (2005), and results showed that adding early reflections hardly had any effect on listening difficulty while a higher level of reverberation resulted in increased difficulty ratings. Increasing the reverberation time could also result in increased difficulty ratings (e.g., Sato et al., 2007), and the reduction of reverberation in virtual classrooms due to treatment or occupation could have positive effects on perceived listening difficulty (Prodi et al., 2010). The addition of construction noise to an existing traffic noise situation in a simulated open space environment could increase the listening difficulty rating, as the combined noise condition was perceived significantly more effortful than traffic noise alone, but the rise in listening difficulty depended on the characteristics (i.e., stationary or impulsive) of the construction noise (Lee and Jeon, 2011).

Paired comparisons to access ease of listening for speech in noise processed with different array processing algorithms in a headband hearing aid have been used by Greenberg, Desloge and Zurek (2003). Results revealed significant effects of algorithm and significant algorithm/noise type interactions and an overall preference for array-processing algorithms over the binaural reference condition.

While ratings of listening effort or difficulty were obtained in an experimental setup, questionnaires assessed listening effort of subject groups in everyday situations. Meis and Gabriel (2001) developed a questionnaire with open and closed questions to measure listening effort perceived during 15 different everyday situations. They tested the questionnaire with subjects with mild, moderate or high-grade hearing impairment who were asked to rate the perceived effort with and without hearing aid use on a 7-point scale. The results indicated that the use of a hearing aid significantly reduced hearing effort compared to unaided listening. Furthermore, the effort expended to listening without hearing aid was dependent on the level of hearing impairment and was most effortful for highly impaired subjects while being least effortful for mildly hearing impaired subjects.

Another questionnaire which also assessed listening effort was developed by Gatehouse and Noble (2004). The »Speech, Spatial and Qualities of Hearing Scale« (SSQ) was designed to measure a range of hearing disabilities by rating the difficulty experienced in different situations on a 10-point scale. However, of the 49 questions about listening to speech, localization of sounds and different sound qualities, only three dealt with the effort during listening (i.e., the »effort of conversation«, the »need to concentrate when listening« and the »ability to ignore competing sounds«). Results from the study showed that the effort of conversation and the need to concentrate were rated similar (4.0 and 3.7, respectively) while the ability to ignore other sounds was rated 5.3 (i.e., less effort). The SSQ has already been used in other studies to investigate different aspects of listening in HI and cochlear-implant subjects (e.g., Noble and Gatehouse, 2006; Noble et al., 2008). Other types of questionnaires (e.g., the hearing aid use log) were also used to obtain ease of listening ratings during hearing aid testing, showing that HI subjects rated the ease of listening as significantly less when they were fitted with one directional and one omni-directional hearing aid compared to two omni-directional hearing aid fittings (Cord et al., 2007).

Summary and discussion

Studies of listening effort presented in this review could be divided into three main types of measurement: measurements of physiological reactions, measurements of cognitive performance or subjective ratings (direct scaling of listening effort or questionnaires). All three types of studies differed in several aspects.

Physiological measurements

Studies involving physiological measurements of listening effort recorded either changes in autonomic body reactions (e.g., the dilation of the pupil, skin temperature etc.) or changes in brain activity (e.g., measured by fMRI). Both kinds of changes were involuntary and therefore not prone to subjective judgments. On the downside, many of these studies required a very specific, oftentimes expensive setup (i.e., pupillometric system or fMRI scanner). This setup often also imposed restrictions on the experiments, with pupillometric measurements usually requiring the subjects to have good vision (partially no wearing of glasses allowed) or fMRI experiments disallowing the wearing of hearing aids (due to the use of high magnetic fields).

Most studies using physiological measurements focused only on NH subjects (Hyönä et al., 1995; Engelhardt et al., 2010; Peelle et al., 2010; Piquado et al., 2010; Zekveld et al., 2010; Blackman and Hall, 2011; Mackersie and Cones, 2011; Koelewijn et al., 2012), with only two studies focusing also on HI subjects (Kramer et al., 1997; Zekveld et al., 2011). The most extensively researched physiological reaction was the dilation of the pupil which was used to measure the amount of cognitive load involved in a certain listening situation. Pupil dilation was significantly affected by the SNR when the noise level during speech presentation was increased, showing higher dilations in situations with decreasing SNRs in both NH and HI listeners (e.g., Kramer et al., 1997; Zekveld et al., 2010; Zekveld et al., 2011; Koelewijn et al., 2012). A significant effect of SNR on physiology was found also when measuring brain activity (e.g., Peelle et al., 2010; Blackman and Hall, 2011). The type of background noise could also have an effect on pupil dilation, as the use of a single-talker masking noise resulted in larger dilations than the use of stationary or fluctuating noise (Zekveld et al., 2011; Koelewijn et al., 2012). Pupil dilation was also dependent on the difficulty of the task, with tasks involving more cognitive processing (e.g. translating words into another language) showing higher dilations compared to simpler tasks (e.g., repeating of speech, see Hyönä et al., 1995). The same was true for memorizing longer digit lists or longer sentences (Piquado et al., 2010) and for translating more difficult words (Hyönä et al., 1995). Task difficulty could also affect other physiological measures such as skin conductance (Mackersie and Cones, 2011). Also the language played a role in the size of pupil dilation, with tasks in the non-native language resulting in higher dilations than tasks in the native language (Hyönä et al., 1995). Prosody was also found to influence the size of pupil dilation. In sentences which were syntactically complex the lack of expected prosodic breaks (conflicting prosody condition) resulted in a significantly higher dilation than sentences containing said breaks (cooperating prosody condition; see Engelhardt et al., 2010). Age also had an effect on pupil dilation, with older adults showing significantly larger normalized pupil dilations than younger adults during the retention of digit lists (Piquado et al., 2010); on the other hand, no age effects were found during listening to and the retention of sentences and during digit list and sentence acquisition (Piquado et al., 2010; Zekveld et al., 2011; Koelewijn et al., 2012). Age effects should, however, be interpreted with caution. It seems that at least in the study of Piquado and colleagues (2010), the absolute size of the pupil prior to the experiments differed between younger and older subjects, thus resulting also in different dilations during the retention period. Furthermore, also the relative amount of change in dilation differed between both age groups, forcing the researchers to normalize the data prior to the analysis in order to relate the observed change to the maximal amount of change which was possible in each group. Thus, while the absolute amount of change in pupil dilation for younger and older subjects was different during the experiment, both age groups showed similar relative changes in pupil dilation, indicating that the listening effort in both groups might be similar (Piquado et al., 2010). Changes in hearing acuity also affected pupil dilation, as there was a significant interaction between hearing acuity and SNR indicating that HI listeners benefited less from easier listening conditions than NH listeners (Kramer et al., 1997; Zekveld et al., 2011).

Cognitive performance

The effort required during listening could also be estimated from the changes in cognitive performance in response to changes in the listening conditions. Experiments using cognitive performance rely on both the assumption that adverse listening conditions should translate into lower performance on specific tasks (working memory or secondary task performance) and that this change in performance is related to listening effort. These experiments usually do not require a highly specific setup but they do require subjects to be able to perform these tasks. Furthermore, the overall cognitive performance of the subjects (e.g., in conditions with low listening effort) should be taken into consideration before any changes in the listening conditions are made in order to avoid any listening-unrelated performance changes to influence the results. Measures of cognitive performance have already been acquired using dual-task experiments, single-task experiments and experiments involving working memory (recall or complex tasks). Experiments investigating cognitive performance focused on both NH and HI listeners, with a broad range of topics being investigated, ranging from effects of noise to changes due to the use of processing algorithms.

The effects of background noise on cognitive performance were investigated using both working memory and dual task measurements. Secondary task probe reaction time was found to be significantly increased by the presence of background noise (at 6 dB SNR) compared to the quiet condition (Downs and Crum, 1978). Recall of syllables was also significantly influenced by the background condition, but while a noise level of 60 dB SPL (i.e., 5 dB SNR) resulted in a significantly reduced recall compared to the quiet condition, a noise level of 55 dB SPL (i.e., 10 dB SNR) dB did not lower the recall performance significantly (Surprenant, 1999).

There were several studies investigating the effects of age on listening effort. Negative influences of age on cognitive performance and/or reaction times were found by the group of Hällgren and Larsby (Hällgren et al., 2005; Larsby et al., 2005). Memory and secondary task performance was also reduced in older adults compared to younger adults (Tun et al., 2009). The effect of age on the listening effort in noise was also measured in a dual-task paradigm using both absolute and relative dual-task costs (Anderson Gosselin and Gagné, 2011; Gosselin and Gagné, 2011). This experiment showed that in addition to absolute measures of dual task costs shown in other experiments (Downs and Crum, 1978; Downs, 1982; Sarampalis et al., 2009; Tun et al., 2009) also relative dual-task costs could be used to investigate listening effort.

Comparisons of the secondary task costs showed that also reduced hearing acuity had a negative influence on listening effort, at least for older subjects (Tun et al., 2009). Similar results were found for the effects of hearing acuity on memory performance (Rakerd et al., 1996). In SVIPS tests, older subjects showed significantly reduced performance in the presence of background noise, and also the reaction time of older adults was significantly increased (Larsby et al., 2005). In HI listeners, the use of a hearing aid significantly reduced probe reaction time (Downs, 1982; Gatehouse and Gordon, 1990) but did not influence accuracy or reaction time in SVIPS tests (Hällgren et al., 2005). Probe reaction times were also affected by the mode of presentation: in monaural listening conditions (i.e., by inserting a plug into one ear) reaction times were significantly increased compared to the binaural (unoccluded) condition when the unoccluded ear was oriented towards the noise and the occluded ear was oriented towards the speech (but not vice versa). The modality in which the speech was presented could also have a significant effect on cognitive performance: significantly increased performance and also significantly increased reaction times were observed in the audiovisual modality compared to the auditory-only modality during SVIPS tests (Hällgren et al., 2005; Larsby et al., 2005) while no effect of modality on secondary task reaction times was seen when the noise level in both modalities was the same (Fraser et al., 2010). Working memory seems also unaffected by modality (Picou et al., 2011). Reverberations and distortions caused by peak clipping negatively influenced the reaction time or the simultaneous speech performance in two experiments (Mackersie et al., 2000; Drgas and Blaszak, 2009).

Subjective ratings of listening effort

While both physiological measurements and cognitive performance rely on indirect measurements of listening effort, subjective ratings use a direct estimation of the effort invested or the difficulty experienced during listening.

So far, studies using subjective ratings focused on NH subjects (e.g., Sato et al., 2008; Prodi et al., 2010; Lee and Jeon, 2011), HI subject (e.g., Humes et al., 1997; Meis and Gabriel, 2001; McAuliffe et al., 2012) or on both (Sato et al., 2007; Schulte et al., 2009; Luts et al., 2010). Ratings of effort (or difficulty) increased with increasing SNR levels (e.g., Schulte et al., 2007; Schulte et al., 2008). The level of memory load, on the other hand, did not influence perceived listening effort (Rönnberg et al., 2011). The type of noise also played a role, as »olnoise« was found to be a more effortful background condition than cafeteria noise (e.g., Schulte et al., 2007; Schulte et al., 2008), and a combined traffic/construction noise was rated significantly more difficult to listen to than the corresponding traffic noise alone (Lee and Jeon, 2011; although part of the effect was probably due to a general increase in noise level). However, the increase of listening difficulty was dependent on the type of construction noise added: While listening difficulty increased with increasing SNR when stationary construction noise was used, there was no significant effect of SNR (at the range tested) when impulsive construction noise was used (Lee and Jeon, 2011).

HI listeners experienced more listening effort than NH listeners (e.g., Luts et al., 2010); while in HI listeners, listening effort could be significantly reduced by using hearing aids (Humes et al., 1999; Meis and Gabriel, 2001). Hearing aid processing algorithms, on the other hand, did not necessarily have much effect on perceived effort: Neither BILL processing nor WDRC compression led to significant changes in effort compared to linear processing (Humes et al., 1997; Humes et al., 1999), neither did cellular phone encoding algorithms have any effect on listening effort in HI listeners (Mackersie et al., 2009).

Algorithms specially designed to reduce noise or increase speech intelligibility had mixed effects: Some noise reduction algorithms led to a reduction in listening effort in drill noise but not in cafeteria noise (Marzinzik and Kollmeier, 1999), a digital noise reduction algorithm led to a reduction in listening effort and difficulty in olnoise (Schulte et al., 2008), other algorithms led to increases or decreases of listening effort multi-talker babble noise (less effort with MWF, more effort with BSS, see Luts et al., 2010). Even the listening effort for different array processing algorithms for a headband hearing aid was investigated, showing that all tested algorithms were preferred over the binaural reference condition (Greenberg et al., 2003).

Several studies investigated the relationship between intelligibility and listening difficulty for different room acoustic conditions (see also Morimoto et al., 2004). Early reflections seemed to have hardly any effect on listening effort – aside from adding energy to the signal - while an increase in the level of late reverberation increased listening difficulty (Sato et al., 2005). Reverberation time and/or the ratio of reverberant to direct sound also seemed to increase the experienced listening difficulty in reverberant sound fields (Sato et al., 2007). Changes in auralization could also have effects on listening effort in virtual room acoustics, as the listening effort in occupied treated rooms was found to be lower than the listening effort in unoccupied untreated rooms (Prodi et al., 2010). Finally, also the effects of the age of the speaker on intelligibility and listening effort in older HI listeners were investigated, showing that listening effort for speech produced by elderly speakers was higher than for speech produced by young speakers (McAuliffe et al., 2012).

To get an overview and summary of the most relevant publications on listening effort methods along the three domains, please see table 1 to 3 of the appendix. As several publications used the same methods, only key publications were considered in the tables. In short, test type, the amount and type of subjects, the focus of the study, and the outcome were reported.

Concluding discussion

All in all, several studies have shown that listening effort is an additional factor, providing additional information to the process of understanding. Both, speech intelligibility and listening effort are correlated with SNR, but differently.

For an objective assessment of the suitability of the methods reported in this review, it is important to keep in mind that when a situation or treatment (e.g. use of a noise reduction algorithm in hearing aids) has failed to show a significant influence it does not necessarily mean that there is no influence at all. The method just might not have been sensitive enough. Therefore, one goal of this literature review was to evaluate which procedure may provide the most practical and sensitive way to measure listening effort. Among the three types of measurement (physiological reactions, cognitive performance or subjective ratings) different methods were described with different results.

Four studies showed that the use of hearing aids does improve listening effort (Downs, 1982; Gatehouse and Gordon, 1990; Meis and Gabriel, 2001; Hällgren et al., 2005). However, as this might be an »easy« task and we are interested in more sensitive methods, it might be more interesting to investigate whether a method can reveal differences in listening effort that correlate with SNR changes.

In pupillometric measurements, significant differences in dilation and listening effort were found between conditions with different intelligibility levels (i.e., SRTs of 50%, 71% or 84%) which corresponded to average changes in SNR of 1.8 to 3.1 dB for stationary noise, 5.0 to 5.8 dB for fluctuating noise and 6.2 to 6.8 for single talker noise (Kramer et al., 1997; Zekveld et al., 2010; Zekveld et al., 2011; Koelewijn et al., 2012). This indicated that - depending on the background noise - even an increase in SNR of 2 dB could potentially be »detected« using this method. However, the studies presented here only investigated SNR conditions in which also speech intelligibility was changed.

In cognitive experiments, an increase of SNR by 5 dB could significantly increase recall in some conditions but not in others (Surprenant, 1999), depending on the serial position of the item to be recalled, but again also here the same SNR change also resulted in a significant change in intelligibility. In listening effort or difficulty ratings, effort decreased with increasing SNR, but it was not reported how much SNR had to increase for the effort to be significantly reduced.

The most difficult - but very interesting - task might be to show an effect of different noise reduction (NR) algorithms on listening effort. However, because NR algorithms are very diverse and range from single channel algorithms using spectral subtraction (e.g., the algorithms SC1 and SC2 in Luts et al., 2010) to multi-channel algorithms using monaural or binaural processing (e.g., monaural: MWF, binaural: BSS and COH in Luts et al., 2010), the expected type and amount of noise reduction due to the processing can be very different.

Therefore, for a better understanding of the sensitivity of this method, the following findings should be re-evaluated according to this. The following papers were able to show that indeed NR algorithms affect the listening effort: Luts and colleagues (2010), Marzinzik and Kollmeier (1999) and Schulte and colleagues (2008, 2009), using a categorical scaling, showed that some multichannel, but also some single channel NR algorithms could reduce perceived listening effort. Greenberg and colleagues (2003) showed that listeners preferred array proces-

Appendix

Publication	Test Type	Subjects	Focus	Outcome
Blackmann and Hall (2011)	fMRI/BOLD	8 NH	acquisition scheme, noise cancellation	Effect of active noise cancellation on sound-related activity.
Engelhardt et al. (2010)	Pupillometry	Exp. 1+2: 18 NH	prosody, visual context	Effects of prosody on dilation, interaction between visual context and prosody
Hyönä et al. (1995)	Pupillometry	18 NH	task difficulty, language, translatability	Effects of task type, language and word translatability on dilation. Interactions between factors. – Effects of task type and translatability on response latencies. Interactions between factors.
Koelewijn et al. (2012)	Pupillometry	24 young + 24 middle-aged NH	SNR, age	Effect of SNR (i.e., intelligibility) and masker type on peak and mean dilation.
Kramer et al. (1997)	Pupillometry	14 NH, 14 HI	hearing acuity, SNR (SRT)	Effects of SNR on dilation, interaction between SNR and & hearing acuity. Effects of age on decrease in dilation between the two lowest SNR conditions.
Mackersie and Cones (2011)	Physiology	15 NH	task difficulty	Effect of task difficulty on EMG and skin conductance but not on skin temperature and heart rate.
Schulte et al. (2011)	Pupillometry	18 NH	SNR, correlation with perceived effort	Effect of SNR on pupil dilation and perceived effort, correlation between both measurements.
Peelle et al. (2010)	fMRI/BOLD	6 NH	SNR (acquisition scheme)	Neural correlates of listening effort in left superior temporal cortex and left inferior parietal cortex.
Piquado et al. (2010)	Pupillometry	Exp. 1: 15 younger/ 15 older NH Exp. 2: 18 younger/ 18 older NH	age, sentence length, syntax	Exp. 1: Effects of digit list length on increase in dilation during digit list acquisition, effects of list length and age on dilation during list retention. Exp. 2: Effects of sentence length on increase in dilation of younger (but not older) adults during sentence acquisition; effect of sentence length on dilation in older and younger adults during sentence retention; significant effect of syntax on dilation during retention in younger adults
Zekveld et al. (2010)	Pupillometry	38 NH	SNR	Effects of SNR on dilation.
Zekveld et al. (2011)	Pupillometry	38 older NH, 36 older HI	SNR, age, hearing impairment	Effects of SNR and hearing impairment on dilation. Effects of age on response duration.

Table 1: Physiological measurements of listening effort

Tabelle 1: Physiologische Messungen der Höranstrengung

Publication	Test Type	Subjects	Focus	Outcome
Anderson Gosselin and Gagné (2011)	Dual task paradigm	Exp 1+2: 25 young NH, 25 older NH	age	Effect of age on absolute and relative task performance and response time in equated level condition. Effect of age on relative task performance and absolute response time in the equated performance condition.
Downs (1982)	Dual task paradigm	23 HI	w/o hearing aid	Effects of hearing aid on probe reaction times.
Downs and Crum (1978)	Dual task paradigm	49 NH	SNR	Effects of noise but not of speech level on probe reaction times.
Drgas and Blaszak (2009)	Modified single task paradigm	6 NH	reverberation, vocoder bands, FMC	Effects of reverberation time, number of vocoder bands and frequency modulation cutoff (FMC) on reaction time, interactions between factors.
Feuerstein (1992)	Dual task paradigm	48 NH	monaural / binaural	Effect of listening condition on reaction time.
Fraser et al. (2010)	Dual task paradigm	Exp. 1+2: 30 NH	Modality	Exp. 1: Effect of task type (single task/dual task) on performance and reaction time in secondary task. Effect of modality on rating of effort to perform speech task. Exp. 2: Effect of modality and task type on performance and reaction time in secondary task.
Gatehouse and Gordon (1990)	Single task paradigm	44 HI	w/o hearing aid	Effects of hearing aid on reaction time during word and sentence presentation.
Gosselin and Gagné (2011)	Dual task paradigm	25 young NH 25 older NH	age, modality	Proportional dual task cost: Effects of age on tactile task accuracy in audio-only condition. Effects of age on tactile task response time in audiovisual condition. Effect of modality on secondary task accuracy.
Hällgren et al. (2005)	Single task performance / Working memory	12 young 12 older HI	age, modality, w/o hearing aid	Effect of hearing aid use and noise condition in Hagerman speech test, effect of background condition on perceived effort. – Effect of age, modality, and background condition on accuracy in most SVIPS tests. Effect of modality and background condition on reaction time in most tests. Interactions. Effects of modality, hearing aid and background on effort.
Huckvale and Frasi (2010)	Single task paradigm	Exp. 1: 20 NH Exp. 2: 18 NH	w/o noise reduction processing	Exp. 1: Effect of noise but no effect of noise reduction on mean reaction time (typometer) and proofreading performance (proofometer).
Huckvale and Leak (2009)	Single task paradigm	20 NH	w/o noise reduction processing	Effect of noise and digit type but no effect of noise reduction on reaction time in typometer experiment.
Klatte et al. (2007)	Working memory	94 NH	reverberation, background noise	Effect of background noise and reverberation time on recall of word sequences. Effect of reverberation time on performance of complex instructions.
Larsby et al. (2005)	Single task performance / Working memory	12 young NH 12 older NH 12 young HI 12 older HI	age, modality, hearing acuity, noise type	Effect of noise on accuracy and reaction time. Effects of age, hearing, modality (and noise type) on accuracy and reaction time in noise in most tests. Interactions of noise & modality. Effects of hearing, modality and noise but not age on perceived effort.
Mackersie et al. (2000)	Simultaneous sentence test	18 NH	background condition, distortion (peak clipping)	Effect of sentence type and clipping, interaction between both factors. No effect of (low) clipping on sentence type. In short sentences significant effect of sentence type.
Picou et al. (2011)	Working memory	20 NH (scaling: 15)	noise, modality	Effect of noise but no effect of modality on recall and perceived listening effort.
Rakerd et al. (1996)	Dual task paradigm	Exp. 1: 8 young NH, 7 young HI, Exp. 2: 11 young NH, 11 older HI	hearing acuity, age, listening condition (speech or noise)	Exp. 1: Effect of listening condition and hearing acuity on recall. Exp. 2: Effect of listening condition and age on recall. Interaction between subject group and listening condition.
Rönnberg et al. 2011	Dual task paradigm	41 NH	memory load	Effect of memory load level on performance and reaction time. No effect of memory load level on perceived listening effort.
Sarampalis et al. (2009)	Dual task paradigm	Exp 1+2: 25 NH	w/o noise reduction, context	Exp. 1: Effects of noise reduction on recall differed between word types and SNRs. Effect of noise reduction on recall only at one condition. Exp. 2: Effect of SNR on reaction time. Effect of noise reduction on reaction time only for the worst SNR condition.
Surprenant (1999)	Working memory	Exp 1+2: 30 NH	noise, serial position	Effect of noise condition and serial position on syllable recall and interaction between noise and serial position in both experiments.
Tun et al. (2009)	Dual task paradigm	48 young and older NH and HI	age, hearing acuity	Effects of age, task, list type and hearing acuity on recall. Effect of age and task on tracking. Interactions between factors for recall and tracking.

Table 2: Changes in cognitive performance as indicators of listening effort

Tabelle 2: Änderungen der kognitiven Leistung als Indikatoren der Höranstrengung

Publication	Test Type	Subjects	Focus	Outcome / Statistics
Greenberg et al. (2003)	Ease of listening paired comparison	9 HI with array headband aid	w/o array processing algorithms	Effects of processing on ease of listening, preference, algorithm/ noise interaction.
Humes et al. (1997)	MELE	110 HI w/o HA	linear and BILL processing	No effect of processing on magnitude estimates of listening effort (MELE), but interactions between factors. No effect of processing on paired comparisons.
Humes et al. (1999)	MELE	55 HI w/o HA	linear and WDRC compression	Effect of hearing aid use, processing and listening condition on MELE, interaction between hearing aid & listening condition. Significant differences between processing type only in quiet conditions.
Lee and Jeon (2011)	Listening difficulty rating	21 NH	combined noise in open space situations	Effect of combined noise on listening difficulty, size of the effect dependent on noise characteristics of the added noise.
Luts et al. (2010)	Listening effort scaling	38 NH, 71 HI	w/o noise reduction algorithms	Overall effects of test site and subject group on listening effort. Significant effect of hearing impairment on listening effort in unprocessed condition. Significant effect of some algorithms on listening effort.
Mackersie et al. (2009)	Listening effort rating	14 HI	encoding algorithms	Significant effect of amplification and noise on listening effort, no effect of encoding on listening effort.
Marzinzik and Kollmeier (1999)	Ease of listening scaling, paired comparisons	6 NH, 6 HI	noise reduction algorithms	Effect of two out of three algorithms on perceived listening effort of HI subjects, no effects of algorithm in cafeteria noise. – Overall judgment in paired comparison in favor of algorithms.
McAuliffe et al. (2012)	Listening effort scaling	19 older HI	age effects (of the signal)	Effect of speaker age on perceived listening effort.
Meis and Gabriel (2001)	Listening effort questionnaire	100 HI	w/o hearing aid	Effect of hearing aid use on listening effort. Effect of hearing impairment on the amount of listening effort in unaided listening.
Prodi et al. (2010)	Listening difficulty ratings	42 NH	virtual room acoustics	Effect of sound fields on rating of listening difficulty.
Sato et al. (2005)	Listening difficulty ratings	Exp. 1: 14 NH Exp. 2: 13 NH	native/non-native listeners, virtual room acoustics	Exp. 1 No (distinct) effects of early reflections on listening difficulty. No changes in difficulty between native- and non-native listeners. Exp. 2: Effects of reverberation level on difficulty.
Sato et al. (2007)	Listening difficulty ratings	142 older NH and HI	age effects, virtual room acoustics	Increase of difficulty with increasing reverberation and increasing ratio of reverberant to direct sound in some conditions.
Schulte et al. (2007)	Listening effort scaling	Exp. 1: 10 NH, 10 HI, Exp. 2: 8 NH	noise type	Exp. 1+2: Effect of noise type on listening effort.
Schulte et al. (2008)	Listening effort/ listening difficulty scaling	Exp. 1: 10 NH, 20 HI, Exp. 2: 10 HI Exp. 3: 8 NH	SNR, noise type, w/o noise reduction processing	Exp. 1: Effect of noise type on listening difficulty and listening effort. Exp. 2: Effect of noise reduction on listening effort and difficulty. Exp. 3: Effect of noise type on listening difficulty.
Schulte et al. (2009)	Listening effort scaling	40 NH, 72 HI	w/o noise reduction	Effect of some noise reduction algorithms on listening effort.

Table 3: Subjective ratings of listening effort

Tabelle 3: Subjektive Bewertungen der Höranstrengung

sing algorithms over the (unprocessed) reference condition in a paired comparison rating of listening effort. In one study using a dual task methods, Sarampalis, Kalluri and colleagues (2009) showed a significant reduction in reaction times as an effect on NR indicating decreased listening effort.

In this review we discussed 54 publications on listening effort. When examining these publications according to their publication year, the number of publications per year tended to increase with time. In the years 1975 to 1996, a maximum of one publication per year was found. In the years 1997 to 2008, up to four studies were published each year, while in the years 2009, 2010 and 2011 the number of publications was 7, 10 and 8, respectively. This increase clearly shows that listening effort is becoming an increasingly important topic.

Listening effort can be measured quite well in everyday situations by means of questionnaires. As already shown in this review, there are also several methods to measure listening effort in the lab. For future research, it would be very interesting to relate the everyday experience of the (hearing-impaired) listeners to the results from the laboratory experiments.

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