Chapter 6

General discussion
Summary and conclusion

Communication is important in our daily life as it supports relationships between people and as it facilitates the spread of knowledge and information. Many complex sound environments, such as noisy restaurants, bars or traffic noise make a conversation often difficult and effortful. Even normal-hearing listeners have to concentrate and make an effort to follow a conversation. Peoples hearing ability plays a major role in daily life communication situations, especially when the auditory input is altered by hearing impairment. In particular, hearing-impaired listeners often report difficulties understanding speech in background noise and that listening is very hard, tiring, effortful or stressful even when audibility is provided (Kramer et al. 1997; Nachtegaal et al. 2009; Pichora-Fuller, Johnson, and Roodenburg 2009). Hearing-impaired listeners have to spend more effort in order to reach the same speech recognition performance than normal-hearing listeners (Koelewijn et al. 2014). For many years, traditional audiometric measures, assessing a listener’s hearing and speech recognition abilities or the benefit from hearing aids, have been applied as a gold standard. Traditional speech recognition measures are not sensitive enough to reflect changes when performance is at floor or ceiling. By assessing listening effort, challenges in processing speech understanding can be revealed that do occur due to hearing impairment, but would not have been covered with traditional measures. The research presented in this thesis is set to investigate the impact of stimulus related factors, such as SNRs or masker types and individual factors, such as the listener’s hearing and cognitive abilities, that may alter listening effort during speech perception. This chapter summarizes and discusses the most important findings of this dissertation and broader implications for hearing impaired listeners in daily life communication situations will be discussed.

Taken together, the findings of the research presented in this dissertation suggest that the listener’s individual abilities, such as their hearing ability, their cognitive and linguistic abilities together with external factors, such as SNR, masker type or hearing aid processing determine speech recognition performance and correspondingly, listening effort.

Recent evidence on the effect of hearing impairment and hearing aid amplification on listening effort

In Chapter 2, the aim of the study was to investigate whether hearing impairment increases listening effort during speech perception. Secondly, I aimed to clarify whether hearing aids, traditionally applied to rehabilitate from hearing loss, can actually help to reduce listening effort. These two questions were investigated through a systematic literature review on the existing evidence regarding the effect of hearing impairment and hearing aid amplification on listening effort. It was problematic to compare the results directly as they originated from studies with different motivations and research questions. Consequently a great diversity of tasks and test modalities was applied, which illustrates the immaturity of methods to assess listening effort. In summary, evidence obtained by the review indicates that hearing impairment increases listening effort. It was possible to identify scientific evidence across
studies that indicated that hearing aid amplification can help to reduce listening effort. In
general, research on listening effort is still in a developmental stage, aiming for the most
applicable and realistic measurement methods and better understanding of the concept
of listening effort. Additional high quality research is required to strengthen the evidence.

The impact of stimulus-related factors and hearing impairment
on listening effort

Scientific evidence, retrieved by the systematic review (described in Chapter 2), indicates
that hearing impairment increases listening effort. However, this finding was only reliably
confirmed by findings based on EEG measures, as the only one type of physiological
measurement methods. Reliable conclusions and more research is needed to confirm
current findings and to identify the components of listening effort.

The studies described in Chapter 3 and 5 were designed to investigate the relationship
between a listener’s hearing ability, a broad range of SNRs for different masker types
(stationary noise, single-talker and 4-talker masker) on speech recognition performance and
the corresponding pupil response. The motivation to include a large range of SNR levels in all
our experimental studies was based on a number of factors. Recent pupillometry research
has shown a relationship between the pupil response and speech recognition at fixed
performance levels between 50% and 85% correct performance (Zekveld et al. 2010, 2011;
Koelewijn et al. 2012, 2014; Wendt et al. 2016). It was suggested that listening effort may
still change at positive SNR levels where speech recognition performance is high (Wendt
et al. 2016; Wu et al. 2016). A possible explanation could be that the processing of speech
information may require less effort at SNR levels exceeding 100% correct performance.
It was furthermore suggested, that the relationship between listening difficulty and
listening effort also depends on the listener’s motivation (Pichora-Fuller et al. 2016) and
success importance (Richter 2016). The motivation intensity theory has demonstrated the
combined effect of task difficulty and success importance on effort (Richter et al. 2012; Silvia
2012; Barreto et al. 2015). The moderating effect of success importance and the interplay
between listening demand and listening effort was recently demonstrated when effort-
related cardiovascular reactivity was measured in an auditory discrimination task (Richter
2016). High cardiovascular reactivity resulted when the reward or success importance was
high, while low reactivity resulted when the reward and success importance was low. The
level of success importance or reward was found to be crucial in conditions of high listening
demands (Richter 2016). A recent pupillometry study investigated listening effort across a
wide range of listening conditions by measuring the pupil response for speech recognition
masked by interfering speech across an intelligibility range from 0% to 99% correct (Zekveld
& Kramer 2014). Even though the study provided evidence across a range between difficult
and easy listening conditions only four intelligibility conditions were tested. The researchers
focused mainly on examining the pupil response in conditions that are assumed to impose
high processing load for normal-hearing listeners. However, it was not assessed how
different SNR levels across the whole psychometric function would look like when listeners
are hearing-impaired. The differences in the pupil response at fixed intelligibility levels between listeners and the lack of pupil response data corresponding to a range of listening conditions for hearing-impaired listeners motivated us to further investigate the pupil response across a large, detailed range of SNR levels to provide an extended perspective on factors that modulate listening effort.

A broad range of SNRs was tested for each masker type to cover sentence recognition performance varying from 0% to 100% correct, including a range of SNRs typical of everyday life listening conditions. The design choice to include different masker types throughout the experimental studies was based on scientific research suggesting that speech recognition performance and the corresponding pupil response may vary depending on the type of background masker (Koelewijn et al. 2012, 2014; Zekveld et al. 2011; Wendt et al. 2016). Larger pupil response were measured during speech processing in a single-talker masker condition, compared to a fluctuating noise masker (Koelewijn et al. 2012b, 2014) and compared to a stationary noise masker (Koelewijn et al. 2012a). The impact of noise and noise reduction processing during speech recognition in a 4-talker babble masker and a mix of unmodulated speech-shaped noise and a 4-talker babble masker was recently shown by means of speech recognition performance and the pupil response (Wendt et al. 2017). The above described findings suggest that participants might need to expend more listening effort to maintain similar intelligibility performance when dealing with an additive interfering effect of speech information from a masker compared to more energetic masker types. The a-priori knowledge on the effect of different background maskers on effort motivated us to include different masker types in our experiments to investigate whether and how speech recognition and the pupil response would change across the whole psychometric function depending on the masker type. We expected differences in the pupil response and in particular larger pupil responses for the single-talker and the 4-talker masker compared to stationary noise masker condition. The analysis of the outcomes from our experimental studies was separately carried out for each masker type as scientific evidence suggested differences in speech recognition and the pupil response depending on the masker type.

Hearing-impaired listeners and a group of age matched normal-hearing listeners participated. The results suggest an interactive effect between a listener’s hearing ability and the SNR level on the pupil response for both masker types. The comparison between listener groups revealed a different pattern of the pupil response distributed across SNRs. Differences in the pupil response depending on the listener’s hearing ability suggest that listening effort and the allocation of listening effort during speech recognition in everyday life is affected by hearing impairment.

**The impact of cognition and language skills on listening effort**

Empirical evidence seems to suggest an association between the listener’s working memory capacity and their speech recognition performance in background noise (Larsby et al. 2005; Füllgrabe et al. 2015; Füllgrabe and Rosen 2016a; Ohlenforst et al. 2016). A number of studies suggested that better cognitive abilities might be associated with a larger pupil size
during speech recognition in background noise, especially when the listening conditions are difficult (Koelewijn et al., 2012b; Kuchinsky et al. 2016; Wendt et al., 2016; Zekveld et al., 2011; Zekveld & Kramer, 2014). In particular, hearing impaired listeners with better linguistic closure abilities were associated with larger PPDs during speech recognition, compared to listeners with lower linguistic closure skills (Zekveld et al. 2011). Those findings are in line with the ELU model (Rönnberg et al. 2008, 2010, 2013), suggesting that more cognitive capacity, which might be reflected by larger pupil response, is required during speech processing in difficult listening conditions. It seems to be logical to assume that better cognitive abilities might grant better speech recognition performance at a cost of higher listening effort. However, a number of studies did not find that better cognitive abilities were associated with a larger pupil size (Koelewijn et al. 2014b; Zekveld et al. 2013; Zekveld et al. 2014b) or even the opposite effect was found (Ahern & Beatty, 1979, 1981; Koch & Janse, 2016; Wendt et al., 2017). There is evidence suggesting that individual variations in working memory capacity may only explain insignificantly small amounts of variance in speech recognition performance when listeners were young and of normal hearing (Füllgrabe and Rosen, 2016b; Zekveld et al. 2011). Drawing a conclusion on the effect of cognition on listening effort at this point is tricky as evidence is contradictory.

The experimental study in Chapter 3 indicated differences in speech recognition performance and the pupil response depending on the listener’s hearing ability. We assumed that those differences could partly be explained by the listener’s cognitive abilities, which we tested in Chapter 4. With the experimental study in Chapter 4 we aimed to clarify how cognitive abilities, including working memory capacity, inhibition and linguistic closure are associated to speech recognition performance and the corresponding pupil dilation response. For the hearing-impaired and normal-hearing listeners that participated in the study described in Chapter 3, working memory capacity and inhibition of interfering information and linguistic closure were examined and described in Chapter 4. It was hypothesized that better cognitive or linguistic abilities would result in better speech recognition performance and larger task-evoked pupil responses and that hearing-impaired listeners would depend more on their cognitive resources than normal-hearing listeners (Koelewijn et al. 2014, 2012b; Zekveld et al. 2011; Füllgrabe and Rosen, 2016b; Larsby et al. 2005). I assumed that listeners with larger working memory capacity (Van den Meer et al. 2010; Grady, 2012; Koelewijn et al. 2014, 2012b) and better linguistic closure skills (Zekveld et al. 2011) might be able to allocate more cognitive resources to the task and consequently show larger task-evoked PPDs compared to listeners with smaller cognitive abilities. I hypothesized furthermore that the influence of cognitive abilities or linguistic closure abilities would be altered by the SNR condition, such that better cognitive and linguistic abilities would result in relatively large pupil responses at low SNRs (Zekveld and Kramer, 2014). The results show in line with previous findings, that normal-hearing and hearing-impaired listeners with better cognitive abilities show better speech recognition performance and larger pupil responses (Koelewijn et al. 2014; Zekveld, Kramer, and Festen 2011). High cognitive skills, including high working memory capacity, good abilities to inhibit interfering information and good language closure skills may allow the listener to expend more cognitive resources on task performance in challenging conditions. The ability to focus on the target speech and simultaneously to inhibit masking information and to keep the auditory information in mind might be thought
of like ‘noise reduction’ in the human auditory system. Better cognitive and linguistic skills may support a more aggressive ‘noise reduction’ system that allows the listener improved speech recognition performance. It is however effortful to expend an extensive amount of cognitive resources, which is presumably reflected in a larger pupil dilation response.

The impact of noise reduction processing in commercial hearing aids on listening effort
Chapter 5 explored the impact of a noise reduction scheme in commercial hearing aids on speech recognition performance and the pupil dilation measure as indication of listening effort. I examined how these two measures vary across a broad range of SNRs for a stationary noise and a 4-talker masker background. The noise reduction scheme was either set to be active or inactive in the hearing aids, and was tested on a group of experienced hearing aid users. Next to improved speech recognition performance, it was hypothesized that the hearing aid processing may reduce listening effort for the hearing impaired listener. Results from 24 hearing-aid users showed that the noise reduction scheme improved speech recognition performance in noise and a shift of the PPD to lower (more difficult) SNRs. The results suggest for the 4-talker masker that the noise reduction scheme provided a benefit on listening effort (as measured by pupil dilation) beyond that associated with speech recognition. The study described in Chapter 5 addresses an important question in audiology and hearing research. More sophisticated and comprehensive outcome measures of the possible benefit from hearing aid algorithms need to be formed. Measuring pupil response during speech recognition performance, as an indication of listening effort, provides a promising supplement to traditional speech reception accuracy measures. The research presented in the current dissertation provides comprehensive evidence for a better understanding of the characteristics of the pupil dilation measure, particularly with respect to the effects of noise and noise management algorithms.

What can we learn from the current results?

At the time of writing, this dissertation provides the most comprehensive data set on speech recognition performance and corresponding listening effort measures across a broad range of listening conditions. The range of conditions tested and presented within this dissertation is of great value as it provides information on the allocation of effort for a large range of speech intelligibility conditions from impossible to very easy speech recognition. Several major conclusions can be drawn with respect to the overall research questions, namely whether hearing impairment and hearing aid amplification have an impact on speech recognition and listening effort. The current findings suggest that hearing impairment influences the allocation of listening effort, as indicated by the PPD, confirming outcomes from earlier research (Koelewijn et al. 2014; Koelewijn, Zekveld, Festen, and Kramer 2012; Kramer et al. 1997; Zekveld, Kramer, and Festen 2011). The relationship between listening effort and the listener’s hearing ability is however not straight forward. The FUEL framework (Pichora-Fuller et al. 2016) suggests that listening effort is related to the demands of the listening situation, the listener’s hearing ability and the listener’s motivation to perform the task. The task demands were modulated by varying the SNRs and masker types in the experiments. By measuring speech recognition and the corresponding task evoked pupil response, listening
effort was estimated. The estimation of the listener’s motivation is however more complex especially as motivation was not specifically measured in the experiments. The PPD function across SNRs showed a similar bell-shaped pattern in the studies presented in Chapter 3 and 5, which may provide an explanation of the listener’s motivation and how motivation may change with changing task demands. At the range of very positive SNRs, speech recognition performance was high and PPDs were small and somewhat constant, indicating low listening effort. With decreasing SNRs, intelligibility decreased and the corresponding PPD increased rapidly. The listeners were presumably motivated to keep up their high performance in speech recognition and expended an increased amount of effort. The PPD functions showed - independent of the masker type or the listener’s hearing ability - a maximum at an SNR corresponding to approximately 50% correct speech recognition performance. This maximum in the PPD might indicate that most effort is invested at listening conditions that allow the listener to understand half of the presented speech correctly. The transition region between high and low speech intelligibility might trigger the listener’s motivation in an way that keeps them trying as they might feel that investing intense effort is still fruitful (Richter 2016; Eckert, Teubner-Rhodes, and Vaden Jr 2016). When speech recognition becomes impossible and approaches zero, the corresponding pupil response drops as well. The listener might decide that the investment of intense effort brings no further reward and that high speech recognition performance cannot be maintained. There are three major conclusions that should be taken from these findings. First, the measuring across a large range of SNRs is essential to draw conclusion on the allocation of effort across different listening conditions. This is especially important when drawing conclusions on the everyday life of listeners, where sound environments vary constantly. Secondly, the allocation of effort during listening in daily life may differ between normal-hearing and hearing-impaired listeners. Both groups of listeners showed maximum PPDs at certain SNR levels, indicating that the ability to invest intense effort does not depend on the listener’s hearing ability. The maximum PPD for hearing-impaired listeners is presumably shifted towards more positive (easier) SNR conditions, compared to normal-hearing listeners. Finally, even though the current findings relate to and support FUEL (Pichora-Fuller et al. 2016) one cannot expect that maximum effort is always invested at 50% correct performance. Every person has perhaps an ‘ideal working point’ at which the relationship between task reward and task demand motivates the investment of intense effort. However, how an individual values rewards, the importance of higher performance or other triggers such as confidence or task instruction might have an impact on the estimate of effort.

Theoretical implications

The most important tools that listeners have to participate in social interactions during complex communication situations is their residual hearing and their cognitive ability to store, process and filter speech information simultaneously (Roth et al. 2011). However, especially hearing impaired listeners need support when the communication demands become too difficult. Hearing aids cannot directly change the listener’s residual hearing or cognitive abilities. What hearing aids can do is to change the sound that enters the ear by reducing the disturbing secondary sounds to simplify the sound scene, allowing a better
focus on the primary speech sound (Sarampalis et al. 2009). Transferring the benefits of hearing aid technologies, which are typically measured in controlled laboratory conditions to uncalibrated daily life applications is a delicate matter. This transfer can be improved by implicating the three major outcomes from this dissertation, in academia, the hearing aid industry and clinical audiology. Academia should continuously provide evidence across a broad range of listening conditions and extend commonly used SRT measures, aiming for 50% correct speech recognition performance. Evidence closer to the listener’s daily life environment will provide better understanding of the allocation of listening effort (Koch and Janse, 2016; Smeds et al. 2015) and facilitate more meaningful comparisons between different groups of listeners (Xia et al. 2015, 2016) and between signal processing algorithms in hearing aids (Lunner and Sundewall-Thorén 2007; Neher, 2014; Neher et al. 2014; Ng et al. 2013, 2015; Ohlenforst et al. 2016; Wendt et al. 2017). The second major outcome of this dissertation, namely that the allocation of listening effort depends on the listener’s hearing ability, may not be apparent when only a few specific intelligibility levels are compared. The hearing aid industry should implement this knowledge as a reference to improve hearing aid processing and the assessment of their products across a broad range of listening conditions (Le Goff, 2015). In the future, the assessment of listening effort and possible benefits from hearing aid processing should be evaluated for the individuals’ daily life environment. Such real life implementations require collaborations between academia and industrial partners to transfer theoretical knowledge and overcome practical challenges. Implementing findings from this dissertation in clinical audiology is presumably most challenging. In practice, audiologists often have very limited time and resources for the individuals’ hearing aid fitting and the evaluation process of different settings or algorithms. Moreover, measures of listening effort are not commonly applied in clinical audiology. It is still not clear which type of hearing aid processing can most effectively reduce listening effort or if the most beneficial type of hearing aid processing depends on internal factors such as the listener’s hearing or cognitive abilities. It is true, that research on listening effort is still in a developmental stage. However, the inclusion of effort measures in audiology clinics can improve insights on the allocation of effort in daily life, and could result in improved hearing aid fitting for the individual (Pichora-Fuller and Singh, 2006). Moreover better understanding of the relationship between the allocation of listening effort and speech understanding could help to improve auditory training in audiology clinics or hard-of-hearing organizations. Auditory training teaches hearing-impaired listeners and their communication partners, to develop skills for making better use of their residual hearing, to use adaptive devices and hearing aids and therefore improve communications in daily life.

In general, I recommend that researchers in academia, the hearing aid industry and audiologists keep the third major conclusion in mind. We cannot expect that maximum effort, as indicated by the pupil dilation, is always invested around 50% correct performance as individuals are triggered by different circumstances (Richter, 2016; Pichora-Fuller et al. 2016). High quality evidence and the comparability of outcome measures are essential for the developmental stage of research on listening effort. Evidence that is comparable across populations, experimental setups, speech and masker materials and task instructions may impact the results and outcome measures. This demonstrates that the perception of listening effort is not only affected by external factors such as the listening conditions, but it is also sensitive to internal factors such as cognition (Zekveld et al. 2011; Zekveld and
Kramer, 2014) or even emotions. Possible implications of findings within this dissertation may be applicable beyond audiology. The association of changes in the task-evoked pupil response may reveal insights on psychiatric disorders, such as autism, when participants perform cognitive and emotional tasks. Further possible theoretical implications of the current outcomes in people’s daily life could be the evaluation of computer software. The task evoked effort with respect to data handling or computer programs could be evaluated by means of pupillometry.

Overall, the findings within this dissertation suggest that noise reduction processing in hearing aids can significantly improve speech intelligibility and indicate a reduction of listening effort during sentence recognition in background noise. The data suggests that hearing aids can support hearing-impaired listeners by allowing them to regain access to noisy places, which were too difficult and too frustrating to participate in without hearing aids. The knowledge provided by the current thesis is essential for future research in the field of listening effort and for the hearing aid industry to improve the development of better hearing aid algorithms.

Limitations of this thesis

The research presented in this dissertation has taken several approaches to help expand traditional methods of speech reception and hearing aid benefit by the dimension of listening effort. The current dissertation shows that pupillometry can provide reliable measures of listening effort across different labs and participant populations. The importance of estimating listening effort besides speech reception performance measures was verified by obtaining differences in the allocation of effort between normal-hearing and hearing-impaired listeners and by showing that hearing aids can provide benefit even at conditions of high audibility. The assessment of commercial noise reduction processing in hearing aids shows furthermore that measures of listening effort have the potential to influence listener’s daily life. However, there are various factors, which are not part of this dissertation, that are likely to play a role in speech recognition and listening effort. First of all, the experiments were carried out in very controlled experimental setups with calibrated test conditions. Reference and baseline measures are certainly valuable for comparisons. However, noise reduction processing, designed for commercial hearing aids, should ideally be validated in hearing impaired listener’s daily life sound environments. Typical sound environments for hearing-impaired listeners were simulated by including a broad range of SNRs in each experimental study. Nonetheless, the target and interfering masker signals were only presented from fixed positions. This could impact the speech recognition performance and the corresponding measures of the pupil response. The angle and location from which the background maskers were presented might especially affect the noise reduction processing. Another factor that might play a role in speech recognition performance and the pupil response is the adaptation time to the tested hearing aids. The data obtained within the study described in Chapter 5 were collected from experienced hearing aid users. However, those participants had not been given any time to adapt to the tested hearing aid. The hearing aid users might expend additional cognitive resources, feel excitement or uncertainty about the unknown hearing aid. Especially the first test conditions within every experimental session might possibly be
affected by arousal. This should be taken into account when comparing data between the study described in Chapter 3 and Chapter 5, as the hearing aid users in the later study were trained to participate in experimental testing.

**Suggestions for future research**

Suggestions for future research on speech recognition and listening effort are partly guided by the limitations, described in the previous section. The findings from this dissertation provide essential knowledge for a better understanding of the concept of listening effort and factors that modulate effortful listening. This knowledge should now be applied to daily life listening situations of hearing-impaired listeners and hearing aid users. Laboratory test setups with fixed loudspeaker positions can only partly simulate everyday life listening situations. In everyday life, listening situations change all the time and are less predictable, which can be expected to affect speech recognition performance and listening effort. Possible benefits from hearing aid processing should ideally be obtained over a longer period of time. Long term assessment of hearing aid usage can account for the adaptation process to the signal processing and rule out effects of arousal in the pupil response. Furthermore, effects of the adaptation processes can be captured. The current pupil data might be related to changes in the listener’s motivation to stay engaged in the listening task. However, an estimation of the individuals motivation with respect to the listening situation could help to further improve the understanding of the concept of listening effort.