Chapter 1

General introduction
Consequences of hearing impairment and the importance of measuring listening effort.

Hearing impairment is one of the most prevalent disabilities in the European population (Christensen et al. 2009; Roth, Hanebuth, and Probst 2011). Listening to speech in noisy environments is a demanding task, especially when listeners suffer from impaired hearing abilities. When speech understanding is challenging, listeners depend on auditory factors such as their hearing ability and simultaneously on their cognitive abilities such as working memory capacity (Rönnberg et al. 2010). Several types of cognitive resources are required to tackle linguistic and nonlinguistic challenges for successful speech recognition in background noise, including attention, working memory and language processing (Peelle 2012). Hearing-impaired listeners continuously have to expend an extensive amount of cognitive resources to tackle everyday life communication situations. The consequence is, that everyday conversation and listening situations may become very difficult, tiring, effortful and frustrating as the intense application of cognitive resources causes an increased processing load (Jerger et al. 1995; Pichora-Fuller, Johnson, and Roodenburg 2009). Additionally, indirect long term consequences, such as increased levels of distress, lack of energy, increased sick leave, fatigue and an increased need for recovery are typically reported by hearing impaired listeners (Nachtegaal et al. 2009; Hasson et al. 2009). In other words, hearing impairment negatively affects the ability of listeners to communicate in daily life and on the long term, it even puts their health at risk.

It is noteworthy that recent research has shown, that hearing aid users’ daily life listening and communication situations mainly take place at positive signal-to-noise ratios (SNR) at which high speech recognition performance can be reached (Haverkamp et al. 2015). However, even at a high level of performance, hearing-impaired listeners may expend more effort than normal-hearing listeners during speech recognition (Wendt, Hietkamp, and Lunner 2017; Tun, McCoy, and Wingfield 2009; Wingfield, Tun, and McCoy 2005; Rabbitt 1991; Wingfield et al. 2006; McCoy et al. 2005). It is therefore crucial to investigate the concepts of cognitive demands and listening effort to better understand the challenges hearing-impaired listeners face in daily life. The question is, how to assess the amount of effort an individual spends during speech recognition? In the field of audiology and hearing research, audiometric and intelligibility measures, such as word or sentence recognition measures are traditionally used to assess the individuals’ hearing abilities or to evaluate hearing aid benefits. Although commonly applied, those measures are insensitive to listening effort in general and therefore cannot reflect differences or changes in effort (Pichora-Fuller et al. 2016). For example, to preserve comparable performance during speech recognition tasks, participants expend more mental effort in the presence of a single-talker masker than when stationary or fluctuating maskers are presented (Koelewijn, Zekveld, Festen, and Kramer 2012). There is a compelling need to extend commonly applied speech recognition measures with measures of listening effort to gain a complete picture on how the allocation of effort differs across various conditions.

The constant demand for high effort during listening can create a major problem as the hearing-impaired listeners’ social interactions may suffer greatly. People that are
hard of hearing may avoid many social interactions and communication situations, such as bigger gatherings, as speech understanding may be very difficult, frustrating and effortful. The inability to participate in social interactions is typically very frustrating and can even increase the risk for social isolation and depression for the hearing impaired (Pichora-Fuller, Johnson, and Roodenburg 2009; Mick, Kawachi, and Lin 2013; Dawes et al. 2015). Deeper understanding of listening effort during speech recognition is essential on an overall level as the development of better hearing aids can help to improve the rehabilitation from hearing impairment. On an individual level, a deeper understanding of listening effort can help to provide better understanding and support from communication partners, and optimized auditory training and hearing aid fitting.

**Definition of listening effort**

The interpretation of individual differences in speech comprehension and listening effort requires to understand what listening effort actually is. Listening effort has been defined as “the deliberate allocation of mental resources to overcome obstacles to goal pursuit when carrying out a listening task” (Pichora-Fuller et al. 2016). The Framework for Understanding Effortful Listening (FUEL) is an adaptation of Kahneman’s (1973) Capacity Model of Attention in relation to listening effort, extended by a motivation dimension. It incorporates the well-known relationship between cognitive demand and the supply of cognitive capacity and complementary theories of motivation intensity, optimal performance, adapted gain control, fatigue and pleasure. In the FUEL, input-related demands contribute to adverse listening conditions, namely factors affecting the quality of the source signal (e.g. accented speech), the signal transmission (e.g. noise, reverberation, hearing or communication technology), listener abilities (e.g. sensory and cognitive abilities) message (e.g. familiar vocabulary) and context (e.g. visual scene) factors (Pichora-Fuller et al. 2016). Those “input-related demands” modulate the amount of resulting “arousal” to the stimulation, which is determined by the amount of “available capacity”. There are individual differences in the maximum capacity. The “allocation policy” governs how much of the available capacity will be supplied to which activities. There is a limited capacity of mental resources and these resources can be allocated for different tasks. The allocation policy is controlled by four factors, including “automatic attention” or in other words involuntary attention (e.g., allocate capacity to any novel signal; to any object in sudden motion; to any conversation in which one’s name is mentioned), to “intentional intentions” (e.g., listen to the voice on the right ear- phone; look for a redheaded girl with a dog) to the “evaluation of demands” and the “effects of arousal”. The level of arousal is controlled by the demands imposed by the activities in which the organism engages, or prepares to engage and by “input-related demands”, including the intensity of stimulation. Outcome measures, such as cognitive-behavioral, brain, autonomic nervous system, and self-report measures, could be used to index “attention-related responses”. These responses are candidates for measuring listening effort insofar as they support inferences regarding the allocation of capacity or the expending of effort. There are also “automatic arousal responses”, which reflect manifestations of arousal including automatic responses such as pupillary dilation, increased skin conductance, and changes in heart
responses. Factors such as fatigue and (dis)pleasure can influence the evaluation of performance without being the results of performance. Similarly, (dis)pleasure can predispose effort insofar as pleasure in anticipation of and during performing a task can be motivating (Matthen 2016). Importantly, the effects of arousal or motivation level on performance could offer an account for quitting even when the available capacity supply has not been exceeded by the demand for capacity. The FUEL combines core concepts from Kahneman’s (1973) Capacity Model of Attention in relation to listening effort and fatigue and the effect of task demands and motivation dimensions could independently or interactively modulate listening effort. Future research and the findings from this dissertation may help to better understand how all these components, separately and in conjunction, affect listening effort by looking at changes in pupil dilation measures. According to the FUEL (Pichora-Fuller et al. 2016), the concept of listening effort is complex as it depends on the demands of the listening situation, the individual’s hearing ability, but also on the individual’s motivation to keep listening and not to give up. This may for example imply that listeners may decide to spend less effort at various listening conditions. At very low SNRs, where the speech signal is relatively low compared to the background noise, listening may become so difficult that high performance cannot be maintained. The listener may decide to disengage from the task and spend less listening effort, as the application of intense effort brings no further rewards (Richter 2016; Eckert et al. 2016). On the other hand, listening may become very easy at high SNRs and to expend much effort is not required for successful speech recognition.

The most common methods to assess listening effort include subjective, behavioral and physiological measures. Subjective measures, such as questionnaires or self-reports, focus on the individuals perceived effort immediately after a listening task or communication situation, or retrospectively over days. Dual-task paradigms (DTP) are the most commonly applied method for behavioral assessment of listening effort (McGarrigle et al. 2014). Participants typically perform a primary task involving speech recognition performance simultaneously to a secondary task. Commonly applied secondary tasks may involve probe reaction time tasks (Desjardins and Doherty 2013; Desjardins and Doherty 2014; Downs 1982) memory tasks (Feuerstein 1992; Hornsby 2013) or tactile pattern recognition tasks (Gosselin and Gagné 2011). The concept of DTPs is based on the theory of limited cognitive capacity which has to be divided between different tasks (Kahneman 1973b). In other words, lower performance in the secondary task is expected, when the effort or cognitive load to perform the primary task increases (Downs 1982). The third category of measuring listening effort includes physiological methods. Those types of measures aim to capture task evoked changes in the activity of the central and autonomic nervous system (McGarrigle et al. 2014). This can for example be done by functional magnetic response imaging (fMRI), where changes in the blood oxygenation level reflect changes in neural activity. Recent research suggested for example that increased brain activity in certain brain regions can reflect the effect of attention during effortful listening (Wild et al. 2012). When electroencephalography (EEG) is applied to measure listening effort, electrodes on the scalp of the listener can be used to measure changes in mental processing as response to acoustic stimuli (Bernarding et al. 2012; Obleser et al. 2012). The state of the autonomic nervous system is reflected by parasympathetic and sympathetic activity of the nervous system. In research, different measures, such as skin conductance, heart rate variability or pupillometry have been applied.
to study both parasympathetic and sympathetic nervous activity. Measuring changes in the pupil diameter (‘pupillometry’) has previously been used to estimate changes in attention and perception (Laeng, Sirois, and Gredebäck 2012). The pupil diameter reflects changes of the task evoked cognitive load a person is dealing with. A task that includes high cognitive load causes the pupil to dilate until the task demands exceed the individuals available processing resources (Granholm et al. 1996).

Over the past two decades, research in cognitive hearing science and listening effort has developed and grown with fast pace (Arlinger et al. 2009). Awareness has increased that the interaction between auditory and cognitive processing during speech understanding is generally important (Handel and Listening 1991; McAdams and Bigand 1993; Neuhoff 2004), and particularly critical during speech recognition in noise (CHABA 1988; Humes 1996). Based on the fundamental Capacity Model of Attention on listening and speech understanding by Kahneman (Kahneman 1973a), the FUEL framework (Pichora-Fuller et al. 2016) was proposed. The FUEL framework is based on the relationship between cognitive demand and the availability of cognitive resources and incorporates complementary theories of motivation intensity, optimal performance, fatigue, pleasure and adaptive gain control (Pichora-Fuller et al. 2016). The definition and understanding of the concept of listening effort has matured and became more differentiated even over the course of this doctoral study. However, research on listening effort is still in a developmental and experimental stage. Future research is expected to expedite the translation of currently existing and new scientific knowledge about effortful listening.
Using pupillometry to measure listening effort

Choosing an appropriate method to estimate listening effort from such a variety of methods depends on the research questions and the focus of the study. The research carried out within this dissertation aimed to investigate the impact of internal and external factors on speech recognition and the corresponding pupil dilation, as an indication of listening effort. Figure 1 shows on the right hand side the internal factors of interest, including the listeners’ hearing ability, working memory capacity, the ability to inhibit interfering information and lexical closure skills. In the top left corner of Figure 1, external factors that may affect speech recognition and the corresponding pupil dilation are the signal-to-noise ratio of the stimuli, the masker type and hearing aid processing.

I decided to measure changes in the pupil dilation as recent research repeatedly demonstrated that pupillometry can successfully be used to tackle a variety of factors that affect listening effort during speech recognition. Those factors include hearing impairment (Zekveld et al. 2011; Kramer et al. 1997), sentence intelligibility (Zekveld et al. 2011), different masker types (Koelewijn et al. 2012), lexical manipulation (Kuchinsky et al. 2013) and cognitive functions (Zekveld et al. 2011). Measuring changes in the pupil dilation with respect to different listening and speech recognition conditions was the most suitable method for the research questions and the focus of this dissertation.

How can external and internal factors impact speech recognition and the pupil dilation? The impact of hearing impairment and intelligibility on listening effort was repeatedly examined by a number of pupillometry studies (Zekveld et al. 2011; Zekveld et al. 2010; Kramer et al. 1997). The allocation of listening effort for normal-hearing and hearing-impaired listeners during speech recognition in fluctuating background noise was tested at three SNRs (Kramer et al. 1997). Normal-hearing listeners showed larger pupil dilations for low speech intelligibility compared to high speech intelligibility conditions. Interestingly, hearing-impaired listeners were less sensitive to changes of the SNR condition. For the hearing-impaired listeners, less decline in the pupil dilations resulted for the high intelligibility condition, compared to normal-hearing listeners. Normal-hearing listeners seem to perceive more listening effort when speech intelligibility was low. Hearing-impaired listeners on the other hand, seem to be less sensitive to changes of the SNR level and additional easier listening conditions did not seem to be less effortful. The impact of speech intelligibility on speech recognition performance and listening effort was confirmed by a number of pupillometry studies when normal-hearing listeners were included (Zekveld et al. 2011; Zekveld et al. 2010; Zekveld and Kramer 2014). However, speech intelligibility is not only affected by the SNR, but also by the characteristics of masking background signals. Changes in the pupil dilation that reflect the impact of different masker types on listening effort have been measured for normal-hearing and hearing-impaired listeners (Koelewijn et al. 2014; Koelewijn et al. 2012). In a recent study, the influence of different masker types, intelligibility levels and the listeners hearing ability were combined (Koelewijn et al. 2014). For hearing-impaired and normal-hearing listeners speech understanding in the presence of a single-talker masker was more difficult than when a fluctuating noise masker was present. The effect of masker type was additionally reflected by the pupil response, with larger
average pupil dilations measured for the single-talker masker condition. The researchers concluded that normal-hearing listeners may experience less hindrance from interfering speech relative to fluctuating background noise. In summary, it has been repeatedly shown that changes in the pupil dilation can reliably reflect changes of external factors, such as SNR conditions or different masker types. It has been suggested, that internal factors (see Figure 1), such as differences in the individuals working memory capacity may provide explanations for individual differences in speech recognition performance and the allocation of listening effort during speech understanding (Lunner and Sundewall-Thorén 2007; Gatehouse et al. 2003; Pichora-Fuller and Singh 2006; Ohlenforst et al. 2016). Recent research suggested that the listeners cognitive capacity is crucial during speech recognition, given that multiple cognitive processes are engaged, especially during the processing of degraded speech (Lunner et al. 2009; Rönnberg et al. 2010). Cognitive demands during listening typically increase with increasing task difficulty and the listeners have to expend more effort for successful performance. The amount of expended effort may increase until the acoustic challenges of a listening condition become too difficult and listeners disengage from performing the task (Kahneman and Beatty 1966; Granholm et al. 1996; Peavler 1974). Recent research suggested that listeners with lower cognitive capacity may reach their maximum amount of expendable cognitive resources earlier than listeners with high cognitive capacity (Peelle 2017). Lacking available cognitive resources during challenging listening conditions is assumed to cause two different consequences compared to listeners with high cognitive capacity. Either more listening effort needs to be expended to keep up high performance, or task accuracy will decrease and performance will drop (Peelle 2017; Richter 2016). The examination of differences in listeners cognitive capacity may therefore help to explain possible differences in the allocation of effort across a variety of listening conditions. Recently measures of listening effort as an alternative method to evaluate hearing aid benefits next to measures of masked speech recognition performance were applied (Ng et al. 2013; Ng et al. 2015; Rudner et al. 2012). Hearing aids are designed to improve speech intelligibility in quiet and especially in noisy environments where speech understanding is difficult. Digital noise reduction in hearing aids aims to improve the SNR by attenuating interfering background noises. Improved speech intelligibility may be accompanied by a release of cognitive resources and consequently lead to reduced listening effort (Lunner et al. 2009). Interestingly, contradictory results were obtained when the relationship between speech recognition performance, listening effort and hearing aid processing was examined during speech understanding (Neher 2014; Neher et al. 2013; Picou et al. 2013; Sarampalis et al. 2009; Foo et al. 2007; Hornsby 2013; Gatehouse and Gordon 1990). It was for example shown that aggressive noise reduction processing can decrease speech recognition performance and increase listening effort compared to moderate noise reduction processing (Neher et al. 2013). Preference ratings revealed that all listeners preferred some noise reduction processing over inactive noise reduction. It is noteworthy that hearing aid users may perceive hearing aid processing as beneficial and prefer certain algorithms or settings, even though those were not accompanied by significant improvement of speech intelligibility (Picou et al. 2013; Ng et al. 2013; Ng et al. 2015; Brons et al. 2013). The benefit that noise reduction in commercial hearing aids can provide for the hearing-impaired listener was demonstrated by a recent pupillometry study (Wendt et al. 2017). Improved
speech recognition performance, accompanied with reduced listening effort, as indicated by smaller pupil dilations, resulted when hearing-impaired listeners were equipped with commercial hearing aids during speech understanding in background noise (Wendt et al. 2017). Current evidence on individual preferences or reduced listening effort due to hearing aid processing highlights the importance of including measures that capture the allocation of effort when hearing aid processing is provided. Recent research demonstrated that insight on listening effort can reliably be obtained by means of pupillometry. Even though pupillometry has successfully been applied to identify a variety of external and internal factors that can impact listening effort, it is still unknown how the task evoked pupil dilation during speech recognition in background noise differs between hearing-impaired and normal-hearing listeners across a broad range of SNRs. The relationship between a listeners hearing ability and the task evoked pupil dilation during speech recognition as well as the relationship between cognitive skills, speech recognition and listening effort can with the currently available knowledge only partly be explained. Current evidence is only available for a small range of speech intelligibility conditions or not yet confirmed for hearing-impaired listeners. This motivates the investigation of the cause of possible inter-individual differences between listeners.

I hypothesized that hearing impairment may cause more listening effort as processing a degraded acoustic signal may cause a higher demand of cognitive resources. It has repeatedly been suggested that larger working memory capacity, better abilities to inhibit interrupting speech information and better textual closure abilities are related to improved speech recognition performance (Akeroyd 2008; Rönnberg et al. 2010; Zekveld et al. 2011; Koelewijn et al. 2014; Koelewijn et al. 2012; Neher et al. 2009; Neher et al. 2012; Glyde et al. 2013). Therefore I also hypothesized that listeners with better cognitive skills or better linguistic abilities would show better speech recognition performance but larger task-evoked pupil responses (Koelewijn et al. 2014; Koelewijn et al. 2012; Zekveld et al. 2011). Assistive devices, such as hearing aids are designed to compensate for the loss of hearing by improving the audibility of sounds. Improved speech intelligibility in quiet or noisy listening situations may be accompanied by reduced listening effort. The relationship between hearing aid processing and measures of listening effort remains unclear, as contradictory outcomes are reported (Neher 2014; Pals et al. 2013; Hornsby 2013; Picou et al. 2013; Dwyer et al. 2014; Noble and Gatehouse 2006). I was therefore eager to investigate whether commercial hearing aid processing can efficiently help to reduce listening effort for the hearing-impaired listener. Next to improved speech recognition performance, I hypothesized that the hearing aid processing may reduce listening effort for the hearing impaired listener.

Outline of this dissertation and research aims

The goal of this dissertation is to collect evidence about the effects of hearing impairment and hearing aid technologies on speech perception performance and listening effort. It was of particular interest to investigate whether normal-hearing and hearing-impaired listeners expend listening effort differently. I was interested to find out if the listeners hearing ability has a general impact on effortful listening across a variety of listening situations. Perhaps there
is no difference in effort when the listening condition allows high intelligibility performance. On the other hand, challenging listening conditions could cause a more effortful listening condition for those listeners with impaired hearing. And if hearing-impaired listeners do spend more listening effort, is it possible to reduce effort by providing hearing aids?

Three experimental studies were carried out with the aim to answer those questions. The results of this dissertation make an innovative contribution to the listening effort research field by identifying acoustical and individual components that modulate listening effort. In the following, a general outline of the chapters in this doctoral dissertation is provided.

Chapter 2 describes a systematic review of available evidence on the effects of hearing impairment and hearing aid amplification on listening effort. The tested statistical evidence indicated that listening effort was higher for hearing-impaired listeners compared with normal-hearing listeners. It was not possible to identify robust evidence suggesting that hearing aids would help to reduce the expended listening effort. Overall the quality of the examined evidence and the findings of this systematic review did not support firm conclusions. The experimental studies carried out within this dissertation aim to provide more sophisticated evidence for a better understanding of the impact of hearing impairment and hearing aid technologies on listening effort.

Chapter 3 describes an experimental study investigating differences in listening effort, as indicated by the peak pupil dilation (PPD), across a broad range of SNR. I compared hearing-impaired listeners with age matched normal-hearing listeners during speech recognition in a stationary and a single-talker masker background. The results of this study showed that the PPD changed depending on the difficulty of the listening condition and the listeners hearing status. Hearing-impaired listeners had larger PPDs across a range of listening conditions, while normal-hearing listeners had a pronounced maximum PPD across a narrow range of listening conditions. These results demonstrate that the allocation of listening effort during speech recognition across a variety of conditions may be different between normal-hearing and hearing-impaired listeners.

Chapter 4 describes an experimental study investigating whether cognition can explain differences in the PPD and sentence recognition performance during speech recognition in background noise for hearing-impaired and normal-hearing listeners. Based on the first experimental study (see chapter 3) I learned that the allocation of effort during speech understanding may be different for hearing-impaired and normal-hearing listeners. Previous results showed an interactive effect between the listeners hearing status and the SNR on the PPD and sentence recognition performance. The Reading Span Test (RST) (Daneman and Carpenter 1980), the Text Reception Threshold (TRT) and the Size Comparison Span test (SICspan) were additionally carried out during the experiment to investigate whether the differences in the allocation of effort can be explained by different outcome measures for cognitive performance.

Chapter 5 addresses the questions whether a noise reduction scheme in a commercial hearing aid can reduce listening effort for hearing-impaired listeners during speech recognition. Speech recognition performance and the PPD were measured for a group of
experienced hearing aid users wearing commercial hearing aids. A large range of SNRs for a stationary noise masker and a 4-talker masker was again tested. The tested hearing aids included noise reduction processing, and testing was carried out with the noise reduction processing both active and inactive. For both masker types, a beneficial effect of noise reduction on sentence recognition performance and the PPD was observed. Noise reduction resulted in a shift of the performance function and a corresponding shift of the PPD function towards more challenging SNRs. For the multi-talker background masker an additional effect of noise reduction on the PPD may indicate reduced listening effort independent of the difficulty of the listening condition.

Finally, chapter 6, summarizes the results and provides a general discussion of the main findings of this dissertation.