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Toward a more comprehensive understanding of the impact of masker type and signal-to-noise ratio on the pupillary response while performing a speech-in-noise test.

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Abstract

Difficulties arising in everyday speech communication often result from the acoustical environment, which may contain interfering background noise or competing speakers. Thus, listening and understanding speech in noise can be exhausting. Two experiments are presented in the current study that further explored the impact of masker type and Signal-to-Noise Ratio (SNR) on listening effort by means of pupillometry. In both studies, pupillary responses of participants were measured while performing the Danish Hearing in Noise Test (HINT; Nielson and Dau, 2010). The first experiment aimed to replicate and extend earlier observed effects of noise type and semantic interference on listening effort (Koelewijn et al., 2012). The impact of three different masker types, i.e. a fluctuating noise, a 1-talker masker and a 4-talker masker on listening effort was examined at a fixed speech intelligibility. In a second experiment, effects of SNR on listening effort were examined while presenting the HINT sentences across a broad range of fixed SNRs corresponding to intelligibility scores ranging from 100 % to 0 % correct performance. A peak pupil dilation (PPD) was calculated and a Growth Curve Analysis (GCA) was performed to examine listening effort involved in speech recognition as a function of SNR. The results of two experiments showed that the pupil dilation response is highly affected by both masker type and SNR when performing the HINT. The PPD was highest, suggesting the highest level of effort, for speech recognition in the presence of the 1-talker masker in comparison to the 4-talker babble and the fluctuating noise masker. However, the disrupting effect of one competing talker disappeared for intelligibly levels around 50 %. Furthermore, it was demonstrated that the pupillary response strongly varied as a function of SNRs. Listening effort was highest for intermediate SNRs with performance accuracies ranging between 30 % -70 % correct. GCA revealed time-dependent effects of the SNR on the pupillary response that were not reflected in the PPD.

1. INTRODUCTION

Everyday communication requires recognizing and understanding speech in adverse listening situations. External sound sources such as background noise or competing speech can degrade the target speech, which makes following a conversation effortful. Presence of the masking noise demands extra cognitive resources to process, comprehend, and remember speech (Rönnberg et al., 2013). Allocation of additional resources can furthermore lead to higher listening effort, which has recently 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). Consequences of increased effort can be, for example, higher levels of mental distress and fatigue leading to stress, greater need for recovery after work, or increased incidence of stress-related sick leave (Gatehouse and Gordon, 1990; Kramer et al., 2006; Edwards, 2007; Hornsby, 2013).

Within recent years, there has been a growing interest in identifying factors that cause difficulties occurring during speech perception in noise. In audiological research, speech perception is commonly explored using speech audiometry. Traditionally, speech-in-noise tests (e.g. Plomp and Mimpen, 1979; Hagerman, 1982) are applied to measure either the proportion of correctly repeated speech items (intelligibility) - usually single words or single sentences - or the speech reception threshold (SRT) when the speech intelligibility is fixed. Recent studies have demonstrated that measuring speech recognition performance or SRTs within a speech-in-noise test do not capture the whole picture of speech perception. In fact, it has been demonstrated that while maintaining similar intelligibility, listening effort varies depending on acoustical and linguistic aspects of the speech and the masker signal (Koelewijn et al., 2012b; Wendt et al., 2016, 2017). For instance, masker types containing speech/linguistic information might lead to increased effort even with a constant speech intelligibility (Koelewijn et al., 2012a).

Physiological measures, such as pupillometry, have been applied recently to examine the effort accompanying understanding speech in adverse listening environments. It has been shown that listening effort increases together with increasing task demands, which is reflected in an increased pupil size until processing resources are exceeded (Janisse, 1977; Beatty, 1982, Kahnemann and Beatty, 1966; Zekveld et al., 2010, 2011). By applying pupillometry within a speech-in-noise test, several studies explored the impact of hearing status, masker type, or speech intelligibility on listening effort (e.g., Koelewijn et al., 2014; Zekveld et al., 2010; Wendt et al., 2017). Those studies indicated that the impact of masking noise on speech perception and listening effort can be manifold and intricate depending on characteristics of the masker or the SNR, which will be discussed in more detail below. Moreover, the relationship between the performance of the participants and their pupil response during speech processing is not fully captured yet.

Toward the goal of a more comprehensive understanding of listening effort measured by means of pupillary response within a speech-in-noise test, the present work includes two studies that examined the effect of masker type and SNR on effort. Two different experiments will be presented that both applied pupillometry within the Danish Hearing In Noise Test (HINT, Nielsen and Dau 2011): Experiment 1 is exploring the impact of different noise masker types that contain linguistic information on effort when speech intelligibility is kept constant at 50 % and 84 %. Experiment 2 investigates changes in listening effort across a broad range of fixed SNRs corresponding to speech intelligibility between 0 % and 100 % correct recognition. Both experiments were designed to provide insights into the relationship between listening effort (reflected in the pupillary response) and recognition performance (as indicated by the SRT or %-correct performance) using the HINT test across a wide range of acoustic scenarios.

About the impact of the masker type on listening effort:

Generally, two different ways have been distinguished in how the masker signal interferes with the speech signal. If the masker signal coincides in spectrum and time with the speech signal, it is referred to as *energetic masking* (Pollack, 1975; Brungart et al., 2001). Energetic masking is supposed to take place at more peripheral stages of processing. All masking that is not considered as energetic masking and occurs at a more central processing stage is often designated as *informational masking* (Pollack, 1975). Many attempts have been made to disentangle the impact of energetic and informational masking on auditory processing by using different types of maskers (Festen and Plomp, 1990; Hygge et al., 1992; Brungart et al., 2001). In particular, speech-on-speech masking has been of interest when studying speech perception. The interfering speech signal leads to an informational masking effect due to its lexical and semantic content that creates contextual overlap with the target speech (Kidd et al., 2008). However, the interfering content seems to have only little influence on the intelligibility of the target speech. Festen and Plomp (1990) compared speech recognition for three different types of masker, namely a stationary noise, a fluctuating noise and a 1-talker masker. It was reported that the temporal dips of the interfering masker led to a better recognition performance in the presence of a fluctuating noise compared to a stationary noise masker. In addition, recognition performance for speech masked by a 1-talker masker was comparable to the performance for the fluctuating noise masker. Interestingly, at low fixed intelligibility (e.g., 50 %) participants have even shown lower (better) SRT scores for the 1-talker masker compared to the fluctuating noise masker (Festen and Plomp, 1990; Koelewijn et al., 2012b). While the effect of competing linguistic information on the speech recognition performance seems to be rather small and sometimes beneficial, it has been demonstrated that its impact on listening effort is major. Koelewijn et al. (2012a, b) examined the pupillary response within a Dutch speech-in-noise test (Versfeld et al., 2000) for three different masker types. The authors demonstrated significantly larger pupil dilation responses for speech masked by a 1-talker masker

compared to fluctuating noise and/or stationary noise. As concluded by the authors, this increase in effort was mainly explained by the semantic inference with the target speech.

Unfortunately, the design used by Koelewijn et al. (2012) did not allow to distinguish between the masking based on voice characteristics (e.g., timbre, fundamental frequencies) and the actual semantic content. This was due to the fact that the fluctuating noise used in this study only contained the speech envelopes while voice characteristics, which enable us to recognize human speech (even for unknown languages) and let us to tell different voices apart, were not preserved. Hence, these voice characteristics available in the 1-talker masker could explain the observed effect rather than the linguistic information. Some studies have indicated that for babble maskers comprising up to three competing talkers, masking is still highly affected by individual voice characteristics of the talker, whereas for four or even more competing talkers the characteristics of the individual voices become less prominent (Simpson and Cooke, 2005). At the same time, several studies indicated that the intelligibility of the target sentence decreases with increasing number of competing talkers (Simpson and Cooke, 2005; Rosen et al., 2013). This has to be related to the decreasing possibility of listening into the dips since the envelope of the summed signal starts to smooth out with an increasing number of talkers. However, not so much is known about how listening effort changes with more than one interfering talker in the background.

The goal of Experiment 1 was to disentangle the impact of linguistic information (semantic interference) and voice characteristics on listening effort and performance (i.e. SRTs) measured within the Danish HINT. This by examining the impact of different masker types including a 1-talker vs a 4-talker masker on listening effort. For that purpose, an experiment similar to Koelewijn et al. (2012) was conducted. Listening effort was measured by means of pupil dilation and three different masker types were used (a fluctuating noise, a 1-talker and a 4-talker masker). By using a 4-talker masker in contrast to a 1-talker masker, the SRT was expected to be higher (worse) due

reduced opportunities of listening in the dips. At the same time, linguistic information provided by the 4-talker masker was considered to be less audible than for the 1-talker masker, which should lead to less semantic interference and, hence, a smaller pupil dilation response. Consequently, it was hypothesized that listening effort is highest for speech recognition within the 1-talker masker compared to the 4-talker masker (H1), while at the same time, the 4-talker babble was expected to result in higher (worse) SRT due to a smaller beneficial effect of dip listening (H2).

About the impact of speech intelligibility and SNR on listening effort:

Recent studies indicated that listening effort changed in a non-linear way with decreasing SNRs. Ohlenforst et al. (2017) explored the impact of hearing-impairment on listening effort as a function of SNRs for speech recognition in noise. Peak pupil dilations (PPD) were measured for participants performing a speech-in-noise test at eight different SNRs. The authors reported increased PPDs, suggesting higher listening effort, with decreasing SNRs. Interestingly, the pupil dilation reached a maximum value until speech recognition performance was around 40-50 %. When recognition decreased even further (i.e. to < 40 % correct recognition) the pupil dilation dropped again. This decline in pupil dilation was interpreted as a sign of giving up because listening might become too difficult in those conditions, which is supported by the Framework for Understanding Effortful Listening (FUEL, see Pichora-Fuller et al., 2016).

The FUEL assumes that listening effort is not only affected by the task demands, but further by the individual's motivation to complete the task. When task demands increase, due to decreasing SNRs, more cognitive resources are allocated presumably leading to elevated levels of effort. However, resources are limited and when task demands become too high and benefits are no longer outweighs these costs, signs of "quitting" might be observed (Pichora-Fuller et al., 2016). A non-linear change of the effort in form of an inverted U-shape has further been reported by Wu et al. (2016). The authors measured reaction times within a dual-task paradigm with a primary sentence recognition

task and a secondary (visual) tasks across a range of SNRs. Again, reaction times became shorter and subjective effort ratings lower at lowest SNRs with recognition performance below 50 % indicating reduced effort. Similar findings of a neural activity breakdown with increasing memory loads have been reported in other studies examining alpha power of the electroencephalogram (see e.g. Wisniewski et al., 2017; Sander et al., 2012 for a visual task or Petersen et al., 2015 for an auditory task; McMahon et al., 2016 for combining EEG and pupil dilation) and further by fMRI studies (Reuter-Lorenz and Cappell, 2008; Grady, 2012). Taken together, those studies demonstrated that when testing effort at a few constituent SNRs only, one might not cover the whole pattern of listening effort and its changes across a broader range of listening situations. In particular, the breaking point of listening effort, as indicated by the highest pupil dilation or reaction time was reported at around 40-50 % speech recognition performance, remains undetected.

Moreover, recent studies indicated that changes in effort can be found in listening situations with constant performance levels, which led to the assumption that changes in performance (as indicated by % correct performance or SRT) and listening effort (as indicated by the pupil dilation) are not necessarily related to each other (see Koelewijn et al., 2012a; McGarrigle et al., 2014; Wendt et al., 2017). Those studies indicated that listening effort could point towards problems occurring during speech recognition that are not addressed by performance data and vice versa.

The motivation of Experiment 2 was to expand the finding of Experiment 1 by including a number of important differences. Instead of fixed intelligibility, changes in listening effort were explored within a speech-in-noise test across a wide range of eight different SNRs. Thereby, a wide range of acoustic scenarios can be covered including ecological listening situations with high speech intelligibility (Smeds et al., 2015). Based on previous studies (Ohlenforst et al., 2017; Wu et al., 2016), it was hypothesized that the pupil dilation would change as a function of SNR with having a maximum dilation around 40-50 % speech intelligibility (H3). In order to investigate

196 listening effort in a more realistic acoustic environment, pupillary response was measured within a
197 spatial setup of loudspeaker presenting either a 4-talker babble or a stationary noise while
198 participant performing the Danish HINT test. It was expected that the maximum pupil dilation
199 would occur at lower (negative) SNRs for the 4-talker babble compared to the stationary noise (H4).
200 A further motivation for combining those two studies (Experiment 1 and 2) was towards a better
201 understanding of the pupillary response indicating the listening effort involved in a speech-in-noise
202 test (namely the Danish HINT test; Nielsen and Dau, 2011). For that purpose, the findings of both
203 experiments will be discussed with regard to potential applications of pupillometry within a speech-
204 in-noise test as an assessment tool for clinical populations.
205

206 # 2. EXPERIMENT 1

207 ## 2.1. MATERIALS AND METHODS

208 ### 2.1.1 Participants

209 Nineteen participants (aged from 18 to 63 years, mean 32.7 years, 9 male) with normal hearing
210 participated. They were native Danish speakers and had pure tone hearing thresholds for both ears
211 of 20 dB hearing level (HL) or better for octave frequencies between 125 Hz - 4 kHz and 30 dB HL
212 or better for octave frequencies between 6 - 8 kHz. The participants had no history of eye diseases
213 or eye operations. The experiment was carried out without the use of glasses or contact lenses.
214 Ethical approval for the study was obtained from the Research Ethics Committees of the Capital
215 Region of Denmark.

216 ### 2.1.2. Stimuli and procedure

217 Danish sentences, spoken by a male speaker, from the HINT (Nielsen and Dau, 2011) were
218 presented via headphones with three different maskers, i.e. a 1-talker masker, a 4-talker masker and
219 a temporary fluctuating noise masker. The 1-talker masker consisted of a single female talker

reading text from the newspaper. The masker was created by concatenating two speech streams uttered by two different female speakers reading from a newspaper. All breathing pauses (i.e. speech pauses longer than 50ms) were removed. The masker was furthermore spectrally shaped to obtain the same long-term average frequency spectrum as the target sentences. All speaker specific short-term fluctuations of the masker were maintained. The 4-talker masker was created by overlapping two male and two female talkers (all reading text from a newspaper), of which the audio files had the same long-term average frequency spectrum as the HINT sentences. Finally, the fluctuating masker consisted of a noise with the same average frequency spectrum and similar intensity fluctuations of the HINT sentences. To mimic similar temporal intensity fluctuations, the noise signal was multiplied by the envelope of the HINT sentences for two separate frequency bands below and above 1 kHz (Festen and Plomp, 1990).

HINT sentences were presented with one out of the three different masker audio files. In each trial the masker started 3 s before the onset of each HINT sentence and continued for 3 s after sentence offset. The length of each trial varied depending on the length of the presented HINT sentence, which had a mean duration of about 1.5 s. After masker offset, the participants were asked to repeat back the HINT sentence. The total experiment consisted of six different conditions including three different masker types (fluctuating, 1-talker, and 4-talker) and two different SRTs that were performed in a blocked fashion. To ensure comparable speech intelligibility, every participant performed the test at his or her individual SRTs corresponding to either 84 % or 50 % sentence intelligibility respectively by using a staircase procedure based on full sentence correct scoring. To obtain the SRT at 50 % intelligibility, a 1-up-1-down procedure was applied (Plomp and Mimpen, 1979). After a correct response, the SNR increased by 2 dB and after an incorrect response the SNR decreased by 2 dB. In order to measure the SRT at 84 % intelligibility, a 4-up-1-down procedure was used. For each block, the SNR of the first trial started below threshold (i.e. -

15 dB SNR). The first sentence of each block was repeated until the participant correctly repeated the entire sentence. The sound level of the mixed signal (speech and noise) was constant at 70 dB SPL, regardless of SNR. Each block consisted of 33 trials and took about 15 min. After the second and fourth block, participants had a break of 10 min.

In total, 6 blocks, i.e. one for each condition, with 33 trails each were presented in a randomized order. In addition, participants performed one training block consisting of 30 sentences (10 sentences for each noise masker type) at the beginning of the session. The complete measurement took about 2.5 hours per participant.

2.1.3 Apparatus

During the speech perception task the pupil diameter of both eyes were recorded by an eye-tracker system (iView X RED System, SensoMotoric Instruments, Teltow, Germany) with a sampling rate of 60 Hz. An infrared camera that tracked the eye and head position automatically was placed in front of the listener to record both eyes. The presentation of stimuli was controlled by a PC using MATLAB (MathWorks, Natick, MA) based programming. Auditory signals were routed through a sound card (RME Hammerfall DSB multiface II, Audio AG, Haimhausen, Germany) and presented via closed headphones (Sennheiser HDA 200, Wedemark, Germany) in a double-walled and acoustics-treated room (IAC Acoustics, Hvidovre, Denmark). The participants were seated 60 cm from the eye-tracker and the luminance in the booth was adapted such that the pupil diameter was around the middle of its dynamic range. The pupil size and pupil x- and y-traces of both eyes were recorded to detect horizontal and vertical eye movements, respectively.

2.1.4. Pupil Data Processing

Pupil data were processed using MATLAB (MathWorks, Natick, MA) in line with a previous study (see Wendt et al., 2017). Pupil traces of the first 3 trials were removed from further analysis. For all remaining traces the mean pupil dilation and standard deviation was calculated from 3 s prior to the

sentence onset until the noise offset. Pupil diameter values more than 3 standard deviations smaller than the mean were coded as eye-blinks. Eye-blinks were removed by a linear interpolation that started about 80 ms before and ended 150 ms after the blinks. Trials that consisted for more than 20 % of their duration of eye-blinks, gross artefacts or missing data were excluded from further analysis. A moving average filter with a symmetric rectangular window of 117 ms length was used to smooth the de-blinked trials and to remove any high-frequency artefacts. All remaining traces were baseline corrected by subtracting the mean pupil size as measured within the 1 s preceding to sentence onset from each individual trace. After baseline correction traces were averaged for each condition. Consistent with previous studies the peak pupil dilation (PPD) was calculated between 3 s and 7.5 s of stimulus presentation (Zekveld et al., 2010, 2011; Koelewijn et al., 2012; Wendt et al., 2017). This time segment was chosen since a local peak of the pupillary response is usually observed within that segment. Furthermore, it is assumed that the listener would process the sentence and prepare the task (repeating back) during that interval. The PPD was calculated for each participant and each condition.

2.2. RESULTS EXPERIMENT 1

2.2.1. Behavioural data

The average SRTs were calculated for all three masker types and both intelligibility scores for each participant. Results for each condition averaged over participants are shown in Figure 1. An ANOVA on the SRTs revealed a main effect of intelligibility ($F[1,18] = 358$, $p < 0.001$) indicated by a significantly higher SRT at 84 % compared to 50 % intelligibility. In addition, a main effect of masker type was shown ($F[1,18] = 285$, $p < 0.001$). No significant interaction between intelligibility and masker type was observed. Post-hoc analysis was performed by t-tests (two-tailed paired samples) and revealed higher thresholds for the 4-talker babble compared to fluctuating noise ($p <$

0.001) and the 1-talker masker ($p < 0.001$). Furthermore, higher SRTs were measured for the fluctuating noise compared to the 1-talker masker ($p < 0.001$).

[FIGURE 1 about here]

2.2.2. Pupillometry

Figure 2 depicts the PPDs averaged across all participants for 50 % and 84 % speech intelligibility and all three masker types (fluctuating noise, 1-talker, and 4-talker).

[FIGURE 2 about here]

An ANOVA on the PPDs revealed an effect of intelligibility ($F[1,18] = 8.85$, $p = 0.008$) indicated by significant higher PPDs at 50 % compared to 84 % intelligibility. In addition, a main effect for masker type ($F[1,18] = 3.90$, $p = 0.029$) and an interaction between masker type and intelligibility were found ($F[1,18] = 3.6$, $p < 0.046$). Post-doc analysis was performed by t-tests (two-tailed paired samples) and revealed higher PPDs at 50 % compared to 84 % intelligibility for the fluctuating noise masker ($p = 0.003$) and the 4-talker masker ($p = 0.005$), but not for the 1-talker masker. Moreover, t-tests performed between masker types at 84 % intelligibility showed larger PPDs for the 1-talker compared to the 4-talker ($p = 0.009$) and the fluctuating noise masker ($p = 0.006$). No differences in the PPDs between the masker types were found at the 50 % speech intelligibility.

2.3. DISCUSSION EXPERIMENT 1

Experiment 1 examined the impact of masker type and intelligibility on the SRT and on the listening effort while performing aHINT. Data indicated a main effect of masker type on the SRTs. A lower (better) SRT was measured for the 1-talker masker compared with the two other masker

types. Moreover, a lower SRT was measured for the fluctuating noise compared to the 4-talker masker. In other words, the lowest reception thresholds were found for the 1-talker masker, slightly higher thresholds for fluctuating noise, and the highest thresholds for the 4-talker masker independent of the intelligibility. These results are in line with previous studies (e.g., Festen and Plomp, 1990, Koelewijn et al., 2012a; Holube et al., 2011).

On basis of the behavioural data, one could argue that those relatively low SRTs observed for the fluctuating noise and 1-talker masker stemmed from an easier differentiation between target and masker signal compared to the 4-talker masker. Both masker types fluctuate in level of which listeners might take advantage by using the temporal minima within the masker signal to detect the relevant speech cues, which is often referred to as *listening-in-the-dips* or *dip-listening* (Miller and Licklider, 1950; Howard-Jones and Rosen, 1993). Amount of the overlapping energy of target and masker increases with increasing number of interfering talkers, which will furthermore reduce the spectro-temporal gaps and, therefore, the possibilities for dip-listening are reduced. Hence, energetic masking is supposed to increase with an increasing number of speakers (e.g. Rosen et al., 2013). This is reflected in the current study by the higher (worse) SRTs for the 4-talker masker compared to the other maskers, which is in line with our hypothesis (H2). Differences in the SRT were further observed between the fluctuating and the 1-talker masker, indicated by lower (better) SRTs for the fluctuating noise. Those differences have been reported before and might result due to semantic interference during the recognition of speech in the presence of an interfering talker (e.g. Koelewijn et al., 2012a).

In contrast to what might be expected based on a relatively low SRT in the 1-talker masker condition, the pupil data showed the largest PPD for the 1-talker masker compared with the two other masker types when the presentation level of the masker was relatively low (84 % intelligibility). On the assumption that a higher pupil dilation is indicating higher effort, those

results suggest that the participants allocated more resources when the speech was masked by one interfering talker. Increased effort in the presence of one competing talker independent of the SRT has been demonstrated before (Koelewijn et al., 2012a, b, 2014; Ohlenforst et al., 2017) and supports our hypothesis that effort is highest for the 1-talker condition due to highest amount of intelligible interfering linguistic and semantic information (H1). Even though energetic masking is supposed to increase with increasing number of competing talkers, it is assumed that the distinction between target (speech) and noise (4-talker masker) might be facilitated as the background noise becomes less similar to the target signal. At the same time, individual words are less intelligible within the 4-talker babble and, thus, lexical interference might be reduced compared to the 1-talker condition (see e.g. Rosen et al., 2013; Hoen et al., 2007). Our findings support this assumption insofar as the relatively high SRT for the 4-talker babble may indicate the increased energetic masking and reduced opportunity of dip-listening compared to the other maskers. At the same time PPDs were significantly reduced in the 4-talker masker compared to the 1-talker masker which might stem from reduced linguistic interference of the auditory masker. Furthermore, there was no difference found between the PPD measured in the fluctuating noise and the 4-talker babble at 84 % intelligibility, which is also in line with H1.

When the presentation level of the maskers was relatively high (50 % intelligibility), all maskers showed larger PPD compared to the 84 % intelligibility and no differences in the PPDs between the masker types were observed anymore. That is, PPDs were similar for all masker types at the 50 % intelligibility, i.e. in a situation where behavioural data (SRTs) differed dramatically and are not predicting the PPD at all. Note that this is in contrast to what has been reported by Koelewijn et al. (2012a). In their study, the authors observed a pronounced effect of the 1-talker masker on the PPD also at 50 % intelligibility. In general, the results of Experiment 1, in particular

364 the behavioural data and the PPD for the 4-talker masker, emphasize the dissociation between
365 performance and listening effort.

366 *Motivation for Experiment 2*

367 The pupillary response has been commonly measured using speech-in-noise tests by adapting the
368 SNR to examine the listening effort at a controlled speech intelligibility (e.g. 50 % or 84 % correct
369 sentence recognition; Zekveld et al., 2010; Koelewijn et al., 2012a). This adaptive procedure has
370 been applied in Experiment 1 as well. As a consequence, comparisons between the PPDs of the
371 different masker types were drawn at varying SNRs. For instance, the SNRs between the 1-talker
372 and the 4-talker masker differed up to 13 dB at the 50 % intelligibility (approximate -13 dB SNR
373 for the 1-talker vs 0 dB SNR for the 4-talker masker). Recent literature, however, reported that
374 listening effort strongly depends on the SNR (e.g. Ohlenforst et al., 2017; Wu et al., 2016). Those
375 studies indicated that effort is changing across SNRs with highest effort at approximately 50 %
376 correct speech intelligibility. Differences in the PPDs observed in Experiment 1 between the 1-
377 talker and the 4-talker masker might have been occurred due to different masker types, but those
378 effects could also partly stem from differences in the SNR. Hence, distinguishing between the effect
379 of SNR and masker type is not feasible when examining the PPD within an adaptive procedure of
380 varying SNRs to achieve a fixed speech intelligibility as realised in Experiment 1.

381 Experiment 2 aimed to gain insides into the effect of SNR on listening effort under more ecological
382 test conditions. With that goal in mind, two changes were made in the paradigm in Experiment 2.
383 First, pupillary responses were measured at fixed SNRs ranging from -20 dB to 8 dB SNR to cover
384 a broad range of listening situations (and intelligibility scores between 0 – 100 %). Second, stimuli
385 were presented over spatially arranged loudspeakers instead of headphones. This was realized to
386 examine listening effort within a more realistic acoustical setting where spatial cues can be utilized
387 to distinguish between different sources such as interaural time and level differences. Even though

aided listening were not tested in the current study, measuring the pupillary response within a spatial arrangement of loudspeakers is an important step towards testing listeners using hearing-aids. The main focus of Experiment 2 was to investigate the impact of SNR on listening effort, thus pupillary response was measured across eight different SNRs ranging from 0% to 100% correct recognition. The pupillary response was measured with two different masker types, i.e. a 4-talker masker (same as in Experiment 1, but spatially separated) and a stationary noise masker without temporal fluctuations to maximize the masking.

3. EXPERIMENT 2

3.1. MATERIALS AND METHODS

3.1.1. Participants

Twenty-nine listeners (aged from 50 to 77 years, mean 65.7 years, 9 males) with normal hearing participated in Experiment 2. The listeners were native Danish speakers and had average pure tone hearing thresholds of 25 dB hearing level (HL) or better for octave frequencies between 125 Hz - 4 kHz for both ears. Furthermore, the accepted thresholds at 6 kHz were 25 to 55 dB (HL) or better and 25 to 60 dB (HL) or better at 8 kHz, depending on the age of the participants (ISO standard 7029:2017). The participants had no history of eye diseases or eye operations. Ethical approval for the study was obtained from the Research Ethics Committees of the Capital Region of Denmark.

3.1.2. Stimuli and procedure

Danish male sentences from the HINT corpus were presented with two different masker types, i.e. either with a 4-talker masker or a stationary noise masker within a spatial setup of five loudspeakers. The HINT sentences were presented from a loudspeaker positioned in front of the listener at 0 °. The other four peripheral loudspeakers, positioned at +/-90 ° and +/-150 ° with a distance of 1.2 m to the listener's side or back, were presenting the maskers (see Figure 3). The 4-talker masker was realized by presenting four single talkers, including two male and two female

voices, reading a text passage from a newspaper (same as in Experiment 1). Each single-talker was spatially presented via one of the four peripheral loudspeakers in a randomized order, whereby the position of a single-talker with the same gender was balanced across all conditions. Uncorrelated stationary noise was presented through all 4 peripheral loudspeakers as well. Both the 4-talker masker and the stationary noise masker had the same long-term-average spectrum as the HINT sentences. Per masker type, sentences were presented at eight different SNRs ranging between -20 dB and +8 dB, distributed in steps of 4 dB SNR. Note that the goal of this experiment was to cover the whole psychometric function including 0% and 100% correct speech recognition and, thus, pupillary response was measured across a broad range of SNRs including extreme listening situations corresponding to 0% correct recognition. The sound level of the masker was kept constant at 70 dB SPL and the level of the speech was changed according to the SNR condition. The masker levels were kept constant to ensure that the noise would not become too loud at the low SNRs. In addition, changing the noise levels might allow the participants to make assumptions about the upcoming task difficulty. All 16 conditions (eight SNRs vs two masker types) were presented in a block design. Each block contained 25 trials leading to 400 trials per participants. Within each trial, the noise started always 3 s before the sentences onset and ended 3 s after sentence offset. Participants were instructed to repeat back the sentence when the noise stopped.

Participants performed two training blocks for each condition consisting of 20 trials to get familiarized with the testing setup and the procedure. The complete measurement took about 5 hours and was divided into two testing sessions. Within one session, participants performed all eight SNR conditions of one masker type. Half of the participants started with the 4-talker masker, the other half with the stationary noise masker.

[FIGURE 3 about here]

436

437 **3.1.3. Apparatus**

438 The same eye-tracker was used as in Experiment 1 and the presentation of the stimuli was
439 controlled by a PC using MATLAB (MathWorks, Natick, MA) based programming. Auditory
440 signals were routed through the same soundcard as in Experiment 1 but this time were played back
441 via loudspeakers Genelec 8040A (Genelec Oy, Iisalmi, Finland). The experiment was conducted in
442 a double-walled, acoustics-treated IAC-NORDIC (IAC Acoustics, Hvidovre, Denmark) sound
443 booth. Luminance in the booth was kept constant at around 135 lux throughout both testing
444 sessions. For participant with relatively large pupils, the luminance was adapted. The participants
445 were seated 60 cm from the eye-tracker.

446

447 **3.1.4. Pupil Data Processing**

448 For each participant 400 traces were recorded (25 per condition). Pupil data of 29 participants were
449 analysed. Trials that consisted for more than 25 % of their duration of eye-blinks, gross artefacts or
450 missing data were excluded from the further analysis. Due to missing data, two participants were
451 excluded from the further data analysis. Data smoothing, baseline-correction and time-alignment of
452 the data were then performed according to the procedure described in Experiment 1. The PPD was
453 calculated for each participant and each condition.

454

455 **3.2 DATA ANALYSIS**

456 **3.2.1. Linear Mixed Model**

457 Linear mixed models (LMM) were chosen to analyze the performance data and the PPDs. A linear
458 mixed-effects model was built in R-studio (version 1.0.153 with programming language R for
459 Windows version 3.3.3) by using the package lme4 (Bates et al., 2014). The function lmer was

applied to fit LMM to the data. Two different 2-way LMM ANOVAs were performed for statistical comparison of the effect of SNR and masker type, one for the behavioral performance data (% correct performance) and the other for the pupil data. In both models, SNRs were treated as dependent measures, thus as fixed factors, with participants as the repeated measure and, therefore, as a random factor.

3.2.2. Growth Curve Analysis

In experiments on listening effort using the pupillary response, the PPD and/or mean pupil dilation within pre-defined time segments are commonly analysed. However, some limitations have been pointed out with an approach that does explore potential effects by analysing the pupillary response at a particular point in time or for a time-averaged response (Mirman, 2014). As a consequence, recent studies used statistical models to examine the *morphology of the pupillary response* by modelling pupil dilation as a function of time (Winn et al., 2015; Kuchinsky et al., 2013). To account for effects reflected in the time-course of the pupillary response, aforementioned studies applied a Growth Curve Analysis (GCA) as proposed by Mirman (2008). GCA is a multi-level regression technique that fits orthogonal polynomials to time course data in order to analyse time-depended differences between conditions and between individual participants.

In the current study, a third-order (cubic) orthogonal polynomial was applied with fixed effects of SNR. Additionally, all the polynomial terms were included in the model as a random term in order to represent the distributed variance at the individual level. The model was applied to the overall time course of the pupil dilation within a time window starting at 2 s until 7 s of stimulus presentation. The model used a linear combination of three orthogonal polynomials including linear, quadratic and cubic components. The intercept term is supposed to reflect the average height of the curve, linear term refers the overall angle or slope of the curve, and the quadratic term reflects the symmetric rise and fall rate around a primary inflection point (shape of the primary inflection). The

cubic term reflects (asymmetric) differences in the rise and fall and, thus, in the steepness of the curve around inflection points (see Mirman, 2008). Higher-order components were not included in the analysis due to ambiguity in their interpretation as well as due to the fact that they led to an overfitting of the pupil curve (see Książek, 2017). The lme4 package (Bates et al., 2015) was used in R for the GCA computations. The model was applied twice to investigate the effect of SNR on the pupillary response, i.e. once for the stationary noise and another time for the 4-talker masker. The model formula and output can be seen in Table 1 for the stationary masker and Table 3 for the 4-talker masker. Model output was fitted to the data with four different conditions as a reference for a direct statistical comparison. It means that the model fit (AIC, BIC, LogLik) was kept at the same level, yet the fixed effects were printed in a different order with respect to the condition chosen to be a reference.

3.3 RESULTS

[FIGURE 4 about here]

3.3.1. Speech Recognition Performance

Figure 4 shows the performance data, i.e. the averaged recognition scores for the HINT sentences, averaged across all participants for both masker types as a function of SNR. Participants achieved high recognition performance (100 % correct) at the SNRs between +4 and +8 dB SNR. With decreasing SNR (0 dB to -4 dB), recognition dropped rapidly until the participants were able to perform approximately around 5-7 % correct at -12 dB SNR. At -16 and -20 dB SNR, participants' sentence recognition was impossible and performance dropped to 0 % for both masker types. The LMM ANOVA revealed a significant main effect of SNR ($F = 892.0$, $p < 0.001$) and a small but

significant interaction of SNR and masker type ($F = 2.3$, $p = 0.021$). No effect of masker type was found ($p = 0.091$). Post-hoc pairwise t-tests were performed to examine the effect of masker type on the recognition performance between 8 different SNRs (Bonferroni corrected $p = 0.006$ for pairwise t-tests). Significant differences between the two masker types were only revealed at 4 dB SNR ($p = 0.004$), indicating a lower recognition performance for the 4-talker masker.

3.3.2 Pupil Data

Linear Mixed Model

Figure 5 depicts the PPD for the stationary noise masker and Figure 6 shows the PPD for the 4-talker masker as a function of SNRs. For both masker types, the PPD converged to small values at SNRs between 4 and 8 dB corresponding to high performance that almost reach 100 % speech intelligibility. With decreasing SNR, PPD gradually increased and reached maximum PPDs between -4 dB and -8 dB SNR. The corresponding sentence recognition was at approximately between 30 % (at – 8 dB SNR) and 70 % (at -4 dB SNR) correct performance. With SNR decreasing below -8 dB SNR, the PPDs dropped again successively and reached a minimum at –20 dB SNR corresponding to 0 % speech recognition.

[FIGURE 5 about here]

[FIGURE 6 about here]

A 2-way LMM ANOVA was tested including the SNR and the masker type as fixed factors on the PPD. A significant main effect of the SNR ($F = 25.9$, $p < 0.001$) and a significant main effect of the masker type ($F = 6.7$, $p < 0.01$) were found. However, no interaction between SNR and masker type was revealed ($p = 0.9$). Pairwise t-tests were performed on the PPD between adjoining SNRs

(Bonferroni corrected p = 0.006 for pairwise t-tests). For the stationary noise masker, significant differences in the PPDs were revealed between -16 and -12 dB SNR (p = 0.004), between -12 and -8 dB SNR (p = 0.001), between -4 and 0 dB SNR (p = 0.001), and between 0 and 4 dB SNR (p = 0.003). Note that there were no differences between -20 and -16 dB SNR (p = 0.154), between -8 and -4 dB SNR (p = 0.570), and between 4 and 8 dB SNR (p = 0.797).

For the 4-talker masker, significant differences were found between -12 and -8 dB SNR (p < 0.001) and between -4 and 0 dB SNR (p = 0.001). Note that no differences between -20 and -16 dB SNR (p = 0.141), between -16 and -12 dB SNR (p = 0.223), between -8 and -4 dB SNR (p = 0.664), and between 4 and 8 dB SNR (p = 0.750) were found.

[FIGURE 7 about here]

[FIGURE 8 about here]

Growth Curve Analysis

The pupil curves for both masker types are depicted in Figure 7 (stationary noise) and Figure 8 (4-talker). Two different analysis were carried out, one for each masker type. A first analysis was carried for the stationary masker. The model formula, the model fit, and the output for the GCA are presented in Table 1. GCA demonstrated a main effect of SNR on all terms depending on the reference condition (see Table 1), which will be discussed more detailed in the following. A significant effect was found for the intercept (p < 0.05) and the linear term (p < 0.001) for all reference conditions. Furthermore, a significant effect of SNR on the pupillary response was

555 revealed on the quadratic term ($p < 0.001$) for three reference conditions (-12, -4 and 4dB SNR as
556 reference) and on the cubic term ($p < 0.001$) for two reference conditions (-12 and -4 dB SNR as
557 reference). Summing up, a GCA demonstrated that the overall height (intercept) and slope of the
558 pupil dilation (linear term) changed with SNRs for the stationary masker. There was also a
559 significant effect on the quadratic and cubic term for three reference conditions, indicating changes
560 in the symmetric rise and fall rate around a central inflection point (quadratic) and a more delayed
561 peak of the response (cubic term) for more unfavorable SNRs.
562 Planned comparisons were made between some SNRs where the PPDs were similar or did not differ
563 significantly (see previous section about the analysis of the PPD data) by using the GCA model (see
564 Table 2). For the stationary noise masker, the GCA revealed significant differences in the overall
565 time course of pupil dilation between -12 and 4 dB SNR in the intercept term ($p < 0.001$), the
566 quadratic term ($p < 0.001$), and the cubic term ($p = 0.013$), indicating a higher overall pupil dilation,
567 a higher acceleration/deceleration around the central inflection point, and a more delayed peak of
568 the response for the -12 SNR condition. Furthermore, effects on the intercept and the linear term
569 were identified between 4 and 8dB SNR, pointing towards a higher average pupil response and a
570 higher slope of the entire pupil response at 4 dB SNR (see Table 2).
571
572
573 *[Table 1 about here]*
574
575 *[Table 2 about here]*
576 A separate GCA analysis was carried out for the 4-talker masker (Table 3). A significant effect of
577 SNR was found for the quadratic term independent of the reference conditions ($p < 0.05$) suggesting
578 that –similar to the stationary noise- the rise and fall rate around a central inflection point changed
579 with decreasing SNRs. In addition, a significant effect of SNR on the cubic term ($p < 0.001$)

indicated that the delay of the peak response changed across SNRs (for conditions with -12, -4 and 4dB SNR as reference). Moreover, a significant effect of SNR on the overall slope (linear term) and on the average height (intercept) of the pupil dilation was revealed for -4 and -12 dB SNR as reference conditions ($p < 0.001$). Similar as for the stationary masker, planned comparisons were performed between some SNR conditions for the 4-talker masker with similar PPDs (cf. Table 4). For the 4-talker masker, the GCA revealed significant differences between -12 and 4dB SNR in the overall height of the pupil dilation (intercept; $p < 0.001$) and the rise and fall rate around the inflection point (quadratic term; $p < 0.001$). Furthermore, the cubic term significantly differed for the comparison between 4 vs 8dB SNR ($p = 0.049$).

[Table 3 about here]

[Table 4 about here]

3.4. DISCUSSION EXPERIMENT 2

The results of Experiment 2 indicated a strong impact of the SNR on the PPDs. Highest PPDs were measured for intermediate SNRs corresponding to 30 %-70 % correct recognition. Lowest PPDs were revealed at higher SNRs due to a more favourable listening condition and also at lower SNRs where listening became impossible (as indicated of the recognition performance). Interestingly, the impact of the masker type was rather small and only small differences were found between the PPDs of different maskers at the corresponding SNRs. Note that this is not in line with our hypothesis (H4), which predicted a maximum pupil dilation at lower (negative) SNRs for the 4-talker babble compared to the stationary noise.

A GCA was applied on the pupillary response independently for both masker types that revealed further (time-dependent) characteristics of the pupil curve are affected by the SNR. For both masker types, differences in the intercept, linear, cubic, and quadratic term were identified depending on the

reference condition. Independent of the reference condition, an impact of SNR on the overall height and the overall slope of the pupillary response occurred for the stationary masker. An effect of SNR on the rise and fall rate around the primary infection was identified for the 4-talker masker independent of the reference condition. Moreover, selected comparisons between some SNR conditions with similar PPDs identified differences in the overall time course of the pupil dilation, which were not necessarily covered by the PPD analysis. For instance, differences were detected at favourable SNRs, i.e. between 4 and 8 dB SNR, in the overall height and slope of the pupil curve for the stationary noise, and in delay in peak of the response for the 4-talker babble. At both SNRs speech intelligibility was very high (with recognition performance at around 100 %) and no significant differences in the PPDs occurred. Further, differences between -12 and 4 dB SNR were found in the overall size of the pupillary response (for both masker types), the overall slope (for the stationary masker) as well as in the steepness of the primary inflection (for the 4-talker masker). Note that in those two conditions, the PPDs were very similar (in particular for the 4-talker masker), however time-depending changes in the pupil dilation were still detectable between the two SNR conditions where the recognition performances differed dramatically (i.e. below 10% at -12dB and above 90% at 4dB SNR). The results encourage the analysis of the overall time course of the pupillary response.

4. GENERAL DISCUSSION

The two experiments of the present study explored the impact of masker type and SNR on the pupil dilation response using the Danish HINT test. Experiment 1 focused on the impact of semantic and linguistic interference on the pupil dilation at fixed speech intelligibility. Experiment 2 examined the pupil dilation as a function of SNR. Both the effect of masker type as well as changes in pupil

627 dilation as a function of SNRs will be discussed in the following. Finally, challenges and some
628 general considerations when combining pupillometry and a speech-in-noise test will be discussed.
629 The results from Experiment 1 showed lowest (best) SRTs for the 1-talker masker, followed by
630 slightly higher SRTs for the fluctuating noise, and highest (worst) SRTs for the 4-talker masker.
631 This was found at 50 % and at 84 % speech intelligibility. These findings are supported by a
632 previous study from Koelewijn et al. (2012a). One could argue that the relatively low SRTs for the
633 1-talker masker originated from a better and easier differentiation between target speech and masker
634 even at similar intelligibility. However, the pupil data showed a larger pupillary response for the 1-
635 talker masker compared with both other masker types, which suggested that more cognitive
636 resources were invested when the noise masker contained intelligible speech information leading to
637 increased listening effort. These results are in line with H1 that predicted an effect of semantic
638 interference of the masker on the pupil response. Interestingly, this impact of maskers containing
639 speech information was only found at 84 % speech intelligibility, which is not in line with
640 Koelewijn et al. (2012a). Furthermore, it was hypothesized that the effect of the energetic masking
641 should be most pronounced with the 4-talker babble (H2). Again, that was in line with the findings
642 of Experiment 1. Higher (worse) SRTs were found within the 4-talker masker condition due to an
643 increased energetic masking. Our results indicate a distinction between the impacts of informational
644 vs energetic masking. Whereas the effect of semantic or linguistic content of the masker was
645 highest on the PPD and thus on listening effort, the effect of energetic masking was most
646 pronounced for the SRT data and less for the pupil data. Furthermore, the distinction between SRT
647 and PPD data further supports the assumption that performance and listening effort are not always
648 related to each other, which is supported by previous studies (Koelewijn et al., 2012a; Mc Garrigle
649 et al., 2014; Wendt et al., 2017). Note that comparisons of PPDs were drawn between listening
650 situations that highly differ in the SNRs, especially when comparing the 4-talker masker to the other

masker conditions. SRTs measured for different masker types differed by almost 13 dB SNR. Literature indicate that the pupillary response can be further affected by the SNRs (Zekveld and Kramer, 2014; Ohlenforst et al., 2017). Hence, a differentiation between the effect of SNR and masker type would not be possible based on the findings in Experiment 1.

Experiment 2 was conducted with the primary goal of exploring the impact of SNR on the pupillary response. The results of Experiment 2 suggested that the PPD changed non-linearly across SNRs in the form of an inverted U-shape: PPD were highest at intermediate SNRs between -8and -4 dB SNR. With increasing SNRs, the PPDs decreased due to gradually decreasing task demands and listening became easier due to a more favourable SNR. In addition, PPDs demonstrated that the highest effort was reached when speech intelligibility was between 30 % and 70 % correct recognition, which is in line with our hypothesis (H3) and previous studies. Zekveld and Kramer (2014) assessed pupil dilation within a speech-in-noise test across a wide range of intelligibility between 0 % to 99 % correct recognition. The authors reported that pupil dilation was largest at intermediate intelligibility. Recently, Ohlenforst et al. (2017) investigated changes in the pupillary response across a range of SNRs for people with normally hearing and with hearing impairment. It was demonstrated that, again, the PPDs showed a peak at around 40 % -50 % correct speech recognition in both stationary noise and in a 1-talker masker. This non-linear trend of listening effort across a broad range of SNRs had been reported by applying other methods and techniques. For instance, Wu et al. (2016) investigated listening effort employing a dual-task paradigm using primary speech recognition task simultaneously with a secondary visual task. Reaction times were measured within the secondary task as an indicator of the listening effort involved in speech recognition. Results indicated that the reaction times changed in form of an inverted U-shape across SNRs, with a maximum reaction time at intermediate SNRs corresponding to intelligibility between 30 % - 50 % correct recognition.

675 Those findings of a non-linear trend of the listening effort as a function of increasing task demands
676 are supporting the FUEL (Pichora-Fuller et al., 2016). The framework is assuming that listening
677 effort involved in speech understanding in noise is mainly modulated by two dimensions: the task-
678 demand dimension and the motivation dimension. Both can be integrative or independently
679 affecting the cognitive resources that are allocated and, thus, the listening effort within a listening
680 task. The demands mainly depend on external factors that are entailed with the input (such as a
681 degraded signal due to noise, but also due to a hearing loss) or the task (e.g. instructions or
682 complexity of the task). The motivation dimension is more internally controlled and depends on the
683 individual's criterial for the importance of success (Pichora-Fuller et al., 2016). In line with FUEL,
684 effort would increase due to changes in the task demands such as with decreasing SNRs from
685 favourable (e.g. between 4and 0 dB SNR) to intermediate SNRs (between -4 and -8 dB SNR). Our
686 data indicated that participants are willing to spend increased effort with decreasing and more
687 unfavourable SNRs covering an intelligibility range between 30 % - 70 %. However, with further
688 decreasing SNRs, task demands escaladed causing a drop in effort, which is probably due to a drop
689 in the motivation. In extreme listening situations, high task demands, as they would be imposed by
690 low (unfavourable) SNRs, could lead to signs of "quitting" or "giving up" (Pichora-Fuller et al.,
691 2016). In other words, understanding and recognizing speech becomes impossible at very low
692 SNRs. This can lead to disengagement which is probably demonstrated in Experiment 2 at -20 or -
693 16 dB SNR. Note that this breaking point would be undetectable by examining the performance
694 data only. Even though the performance was gradually dropping with decreasing SNRs, the point
695 where the effort was peaking – and would drop with further increasing task demands - would not be
696 reflected in the behavioural data. It was furthermore speculated that the fact that the largest
697 pupillary response was observed in ranges around 50% performance levels, might actually suggest

698 that effort peaks in difficulty ranges where listeners could actively change their own performance
699 level within the speech-in-noise test by exerting more effort.
700
701 *Considerations when testing listening effort for speech recognition in noise*
702 Two experiments were presented in the current study, both applying pupillometry together with a
703 speech-in-noise test that is commonly used for speech audiometry. The results suggested that
704 listening effort changed depending on the masker type as well as on the SNR. While the PPD was
705 larger for maskers containing speech, the PPD was further affected by the SNR and seemed to peak
706 between 30-70 % speech intelligibility. This maximum in PPD was referred to as the breaking point
707 since it might indicate the point where –with further increasing demands- effort would drop due to
708 too high task demands and/or dropping motivation. This can be a problem when examining the PPD
709 at a fixed speech intelligibility, since small changes in the SNRs might have a huge impact on the
710 PPDs when testing at or around this breaking point. Furthermore, it would be difficult to evaluate
711 whether smaller PPDs would indicate reduced effort due to lower task demands or whether smaller
712 PPDs point towards reduced effort as a consequence of giving-up. Hence, when investigating the
713 PPDs at fixed intelligibility, changes in PPDs around the 50 % performance level should be
714 interpreted with caution when the SNRs differ between conditions. Furthermore, when investigating
715 an impact of the masker type on effort by means of PPDs, it can be advisable not only to analyse the
716 PPD or the mean pupil dilation, but also to characterize the whole pupil curve. Several approaches
717 have been realized to model changes in pupil dilation over time (Kuchinsky et al., 2013; Mirman,
718 2014; Winn et al., 2015). Our results indicated that by applying the GCA, time-dependent
719 differences in the pupillary response can be detected that were not necessarily reflected in the PPD
720 alone. Furthermore, time-dependent differences in the overall slope of the pupil curve were
721 identified in situations where speech recognition performances were at ceiling and around 100 %

722 performance. This is in line with previous studies that reported of applying GCA to gain a more
723 sensitive pupillary analysis (Kuchinsky et al., 2013, Winn et al., 2015). Even though a GCA has
724 been successfully applied in recent studies, further work is required to gain a better understanding
725 about how terms of the GCA are related to different aspects of listening effort while performing a
726 speech-in-noise test. In other words, there is still a lack of knowledge in interpreting time-
727 dependent differences in a shape of the pupillary curve in terms of effort involved in speech
728 recognition. Other methods have been proposed to investigate time-dependent changes of the pupil
729 dilation. For instance, Winn (2016) analysed both the growth of the pupillary response (dilation)
730 and the reduction of this response (constriction), and pointed to the later as an indicator of the
731 release from effort. He suggested that analysing the constriction of the pupillary response after the
732 presentation of the stimulus can reveal difficulties due to hearing accuracy (cochlear implant user vs
733 normally hearing listener) and spectral degradation (unprocessed speech vs. vocoded speech).
734
735 **5. CONCLUSIONS**
736 Two main observations were replicated in the current study using the HINT test: First, listening
737 effort is highly affected by the masker type. This was reflected by the largest pupil dilation for
738 speech recognition in the presence of a 1-talker masker in comparison to a 4-talker masker and a
739 fluctuating noise masker. Increased effort in the presence of one interfering speaker, however, was
740 not reflected by the SRTs at fixed intelligibility. Second, listening effort changes with SNR.
741 Pupillary response changed non-linearly across a range of fixed SNRs that corresponded to a wide
742 range of speech recognition between 0 % to 100 % correct performances. Pupil dilation was largest
743 for intermediate SNRs. This point indicated maximum effort and was interpreted as a breaking
744 point since effort would drop with decreasing SNRs. Hence, it was suggested that by means of pupil

dilation, effects of motivation or disengagement on listening effort, that were not necessarily reflected by performance measures, were captured during the speech-in-noise test.

Our findings led to two main conclusions that should be considered in light of the experimental methods and data analysis when testing pupillary response within the speech-in-noise test: First, listening effort changes non-monotonically as a function of SNR with highest effort around 50% performance. Thus, changes in the pupillary response at SRTs around 50 % level of performance should be interpreted with caution since they might indicate either lower effort due to reduced task demands or lower effort due to disengagement or giving up. Second, when assessing changes in the pupillary response over time, difficulties arising during speech recognition in noise can be detected that are not necessarily covered by the PPD alone. In general, our data support the assumption that by collecting pupil responses using a (traditional) speech-in-noise test, a more complete picture of difficulties arising from speech recognition in different types of background sound can be obtained.

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FIGURE LEGENDS

Figure 1*: Mean SRTs averaged across participants measured for three different masker types at two different intelligibility scores (50 % and 84 %). Error bars indicate one standard error from the mean.*

Figure 2: *PPD in mm per masker type and intelligibility scores averaged across all participants. Error bars indicate one standard error from the mean.*

Figure 3: *Experimental setup of the loudspeakers. HINT sentences were presented from the loudspeaker in the front (0 °). The masker was presented from the loudspeaker at the side and the back of the listener (+/-90 ° and +/-150 °).*

Figure 4: *Mean recognition scores (in %) for the stationary noise and the 4-talker masker averaged across all participants. Error bars indicate one standard error from the mean.*

Figure 5*: Averaged PPDs and word recognition scores across all participants for the stationary noise masker for eight different SNRs. Error bars indicate one standard error from the mean.*

Figure 6*: Averaged PPDs and word recognition scores across all participants for the 4-talker babble masker for eight different SNRs. Error bars indicate one standard error from the mean.*

Figure 7: *Mean pupil response averaged across participants per SNR in the stationary masker condition. Sentence onset was at 3 s. The baseline value was calculated as the mean pupil value one second preceding the sentence onset (i.e. between 2 s and 3 s).*

Figure 8: *Mean pupil response averaged across participants per SNR in the 4-talke babble masker. Sentence onset was at 3 s. The baseline value was calculated as the mean pupil value one second preceding the sentence onset (i.e. between 2 s and 3 s).*

Table 1: *Linear Mixed-Effects Model formula and output of the GCA for the pupil dilation recorded in conditions with the stationary noise. The effect of SNR on the all terms was tested against 4 different references, i.e. against -20 dB, -12 dB, -4 dB, 4 dB.*

Formula code: PupilDilation ~ (1 + Linear + Quadratic + Cubic) * SNR + (1 + Linear + Quadratic + Cubic| Subject)												
Model fit: AIC: -34546.3; BIC: -34225.3; LogLik: 17316.2; Deviance: -34632.3; Df. resid: 12857												
Terms	Reference: -20dB			Reference: -12dB			Reference: -4dB			Reference: 4dB		
	β	t	p	β	t	p	B	t	p	β	t	p
Intercept	**0.0186**	**2.743**	**0.009****	**0.038**	**5.575**	**<0.001****	**0.063**	**9.215**	**<0.001****	**0.014**	**2.064**	**0.046***
Linear	**0.216**	**3.192**	**0.002****	**0.359**	**5.325**	**<0.001****	**0.633**	**9.379**	**<0.001****	**0.255**	**3.754**	**<0.001****
Quadratic	**-0.118**	**-1.909**	**0.062**	**-0.228**	**-3.681**	**<0.001****	**-0.380**	**-6.14**	**<0.001****	**-0.44**	**-7.066**	**<0.001****
Cubic	-0.039	-0.905	0.369	**-0.142**	**-3.288**	**0.002****	**-0.204**	**-4.71**	**<0.001****	-0.0456	-1.045	0.3

* p<0.05; ** p<0.01.
AIC – Akaike Information Criterion,
BIC – Bayesian Information Criterion,
LogLik – Logarithmic Likelihood,
Deviance- a measure of the goodness of the model fit,
Df. Resid – Degree of Freedom for Residual,

970 ***Table 2:*** *Planned contrasts: The effect on the pupil dilation between chosen SNRs in the stationary*
971 *noise condition. Contrasts adjusted with the multivariate t adjustment.*

Contrast	**-12dB vs. 4dB** **Term: 4 dB, Reference: -12dB**			**-4dB vs. -8dB** **Term:-8dB, Reference: -4dB**			**4dB vs. 8dB** **Term:8dB, Reference: 4dB**		
Terms	β	t	p	β	t	p	β	t	p
Intercept	**-0.024**	**-6.277**	**<0.001****	0.004	0.947	0.343	**-0.010**	**-2.539**	**0.011***
Linear	-0.104	-1.982	0.047	0.004	-0.078	0.938	**-0.132**	**-2.506**	**0.012***
Quadratic	**-0.213**	**-4.212**	**<0.001****	0.081	1.611	0.107	0.051	0.953	0.341
Cubic	**0.097**	**2.474**	**0.013***	-0.0001	-0.012	0.991	0.004	0.113	0.91

972

973 * $p<0.05$; ** $p<0.01$;

974

Table 3: *Linear Mixed-Effects Model formula and output of the GCA for the pupil dilation recorded in conditions with the 4-talker masker. The effect of SNR on the all terms was tested against 4 different references, i.e. against -20 dB, -12 dB, -4 dB, 4 dB.*

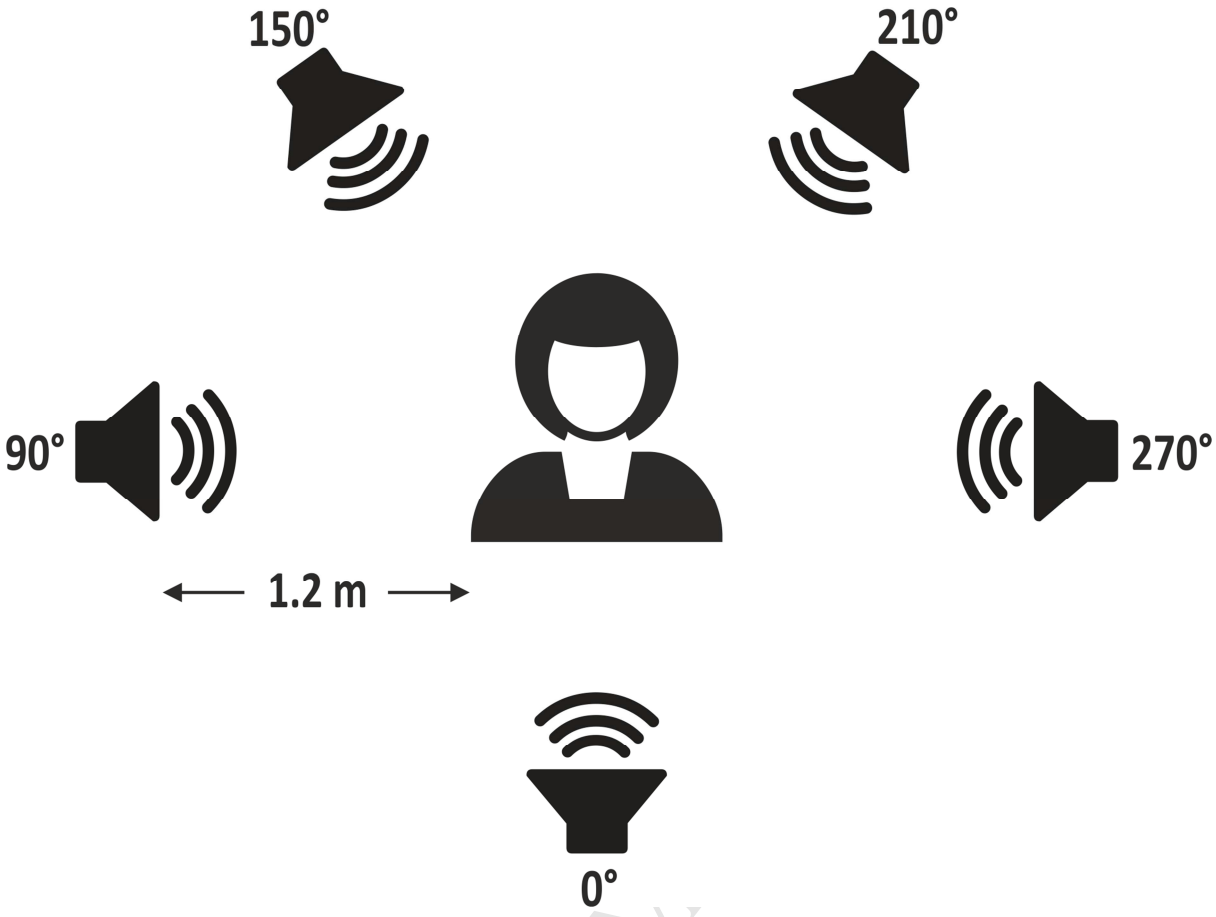
Formula code: PupilDilation ~ (1 + Linear + Quadratic + Cubic) * SNR + (1 + Linear + Quadratic + Cubic| Subject)												
Model fit: AIC: -35375.5; BIC: -35054.5; logLik: 17730.8; Deviance: -35461.5; Df. resid: 12857												
Terms	Reference: -20dB			Reference: -12dB			Reference: -4dB			Reference: 4dB		
	β	t	p	β	t	p	β	t	P	β	t	p
Intercept	0.0057	0.776	0.443	**0.019**	**2.534**	**0.016****	**0.069**	**9.489**	**<0.001****	0.006	0.771	0.446
Linear	0.0462	0.575	0.569	**0.163**	**2.032**	**0.049***	**0.48**	**6.008**	**<0.001****	0.086	1.068	0.292
Quadratic	**-0.143**	**-2.522**	**0.014****	**-0.242**	**-4.291**	**<0.001****	**-0.152**	**-9.440**	**0.009****	**-0.377**	**-6.635**	**<0.001****
Cubic	-0.0594	-1.445	0.153	**-0.141**	**-3.433**	**0.001****	**-0.343**	**-8.347**	**<0.001****	**-0.097**	**-2.342**	**0.022***

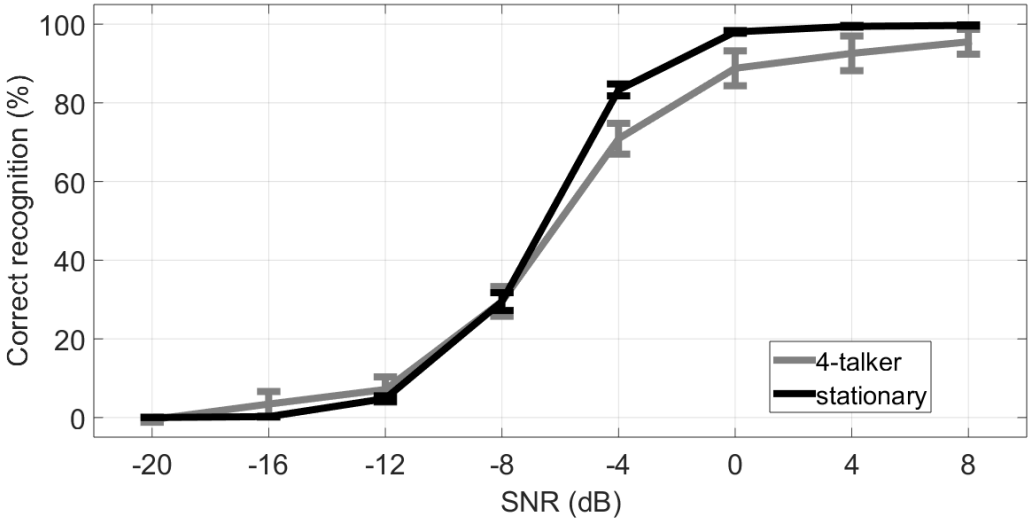
** p<0.05; ** p < 0.01.*
AIC – Akaike Information Criterion,
BIC – Bayesian Information Criterion,
LogLik – Logarithmic Likelihood,
Deviance- a measure of the goodness of the model fit,
Df. Resid – Degree of Freedom for Residuals

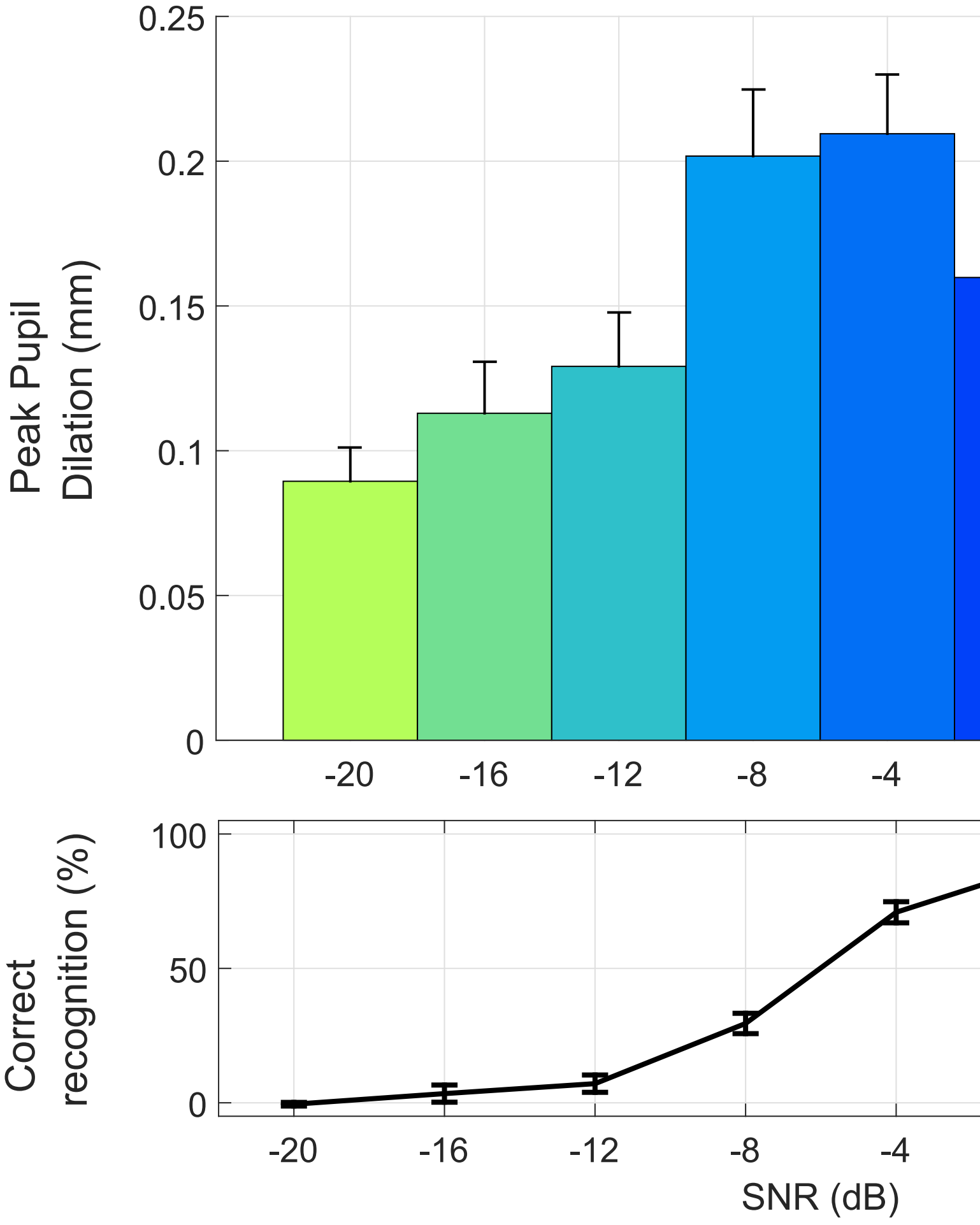
985 ***Table 4:*** *Planned contrasts: The effect on the pupil dilation between the chosen SNRs in the 4-talke*
986 *r masker condition. Contrasts adjusted with the multivariate t adjustment.*
987

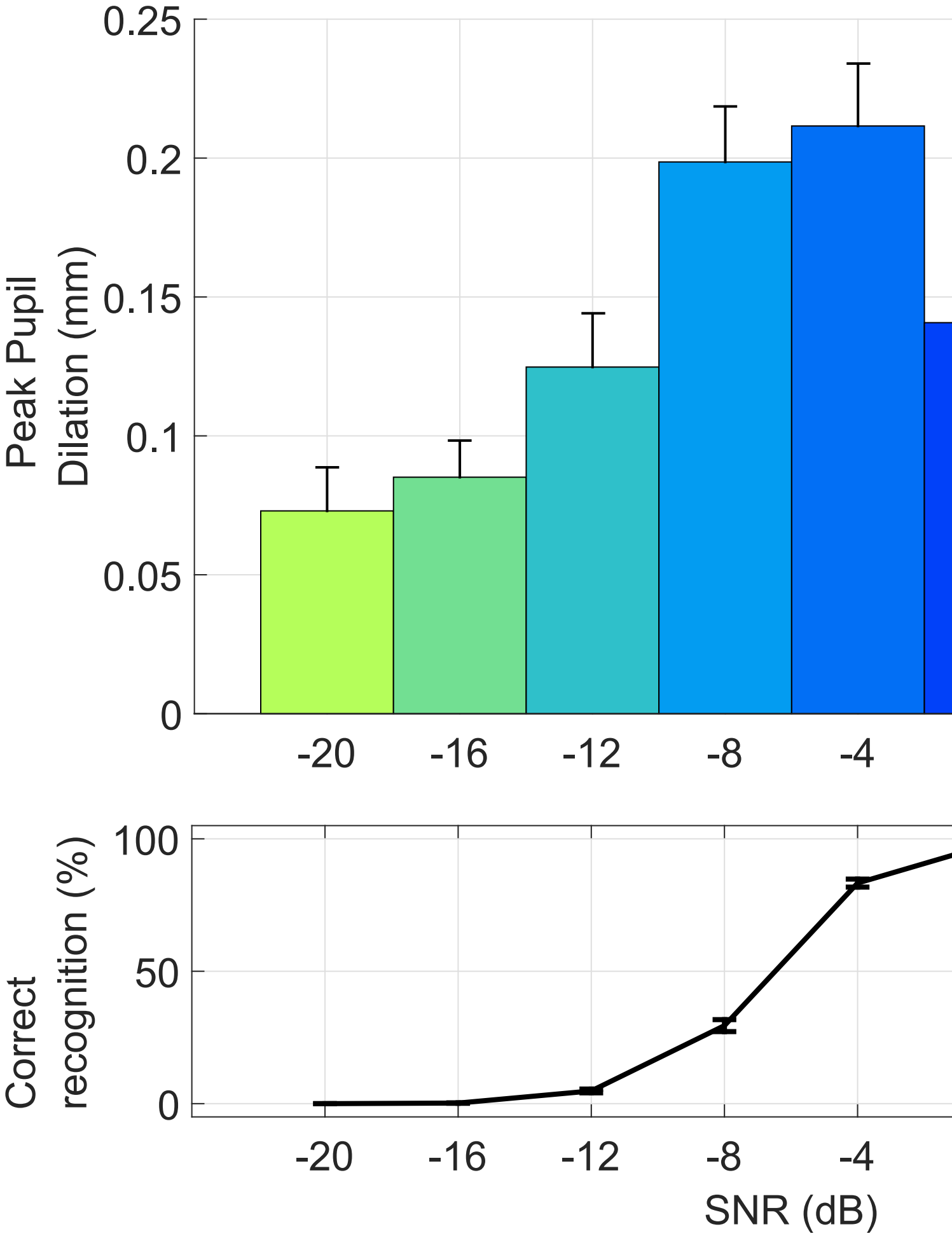
Contrast	**-12dB vs. 4dB** **Term: 4 dB, Reference: -12dB**			**-4dB vs. -8dB** **Term: -8dB, Reference: -4dB**			**4dB vs. 8dB** **Term: 8dB, Reference: 4dB**		
Terms	β	t	p	β	t	p	β	t	p
Intercept	**-0.013**	**-3.532**	**<0.001****	0.003	0.901	0.367	-0.004	-0.963	0.335
Linear	-0.077	-1.512	0.131	0.035	0.700	0.484	0.026	0.508	0.611
Quadratic	**-0.136**	**-2.771**	**0.005****	0.085	1.756	0.079	0.047	0.955	0.34
Cubic	0.044	1.164	0.245	0.012	0.328	0.743	**0.074**	**1.963**	**0.049***

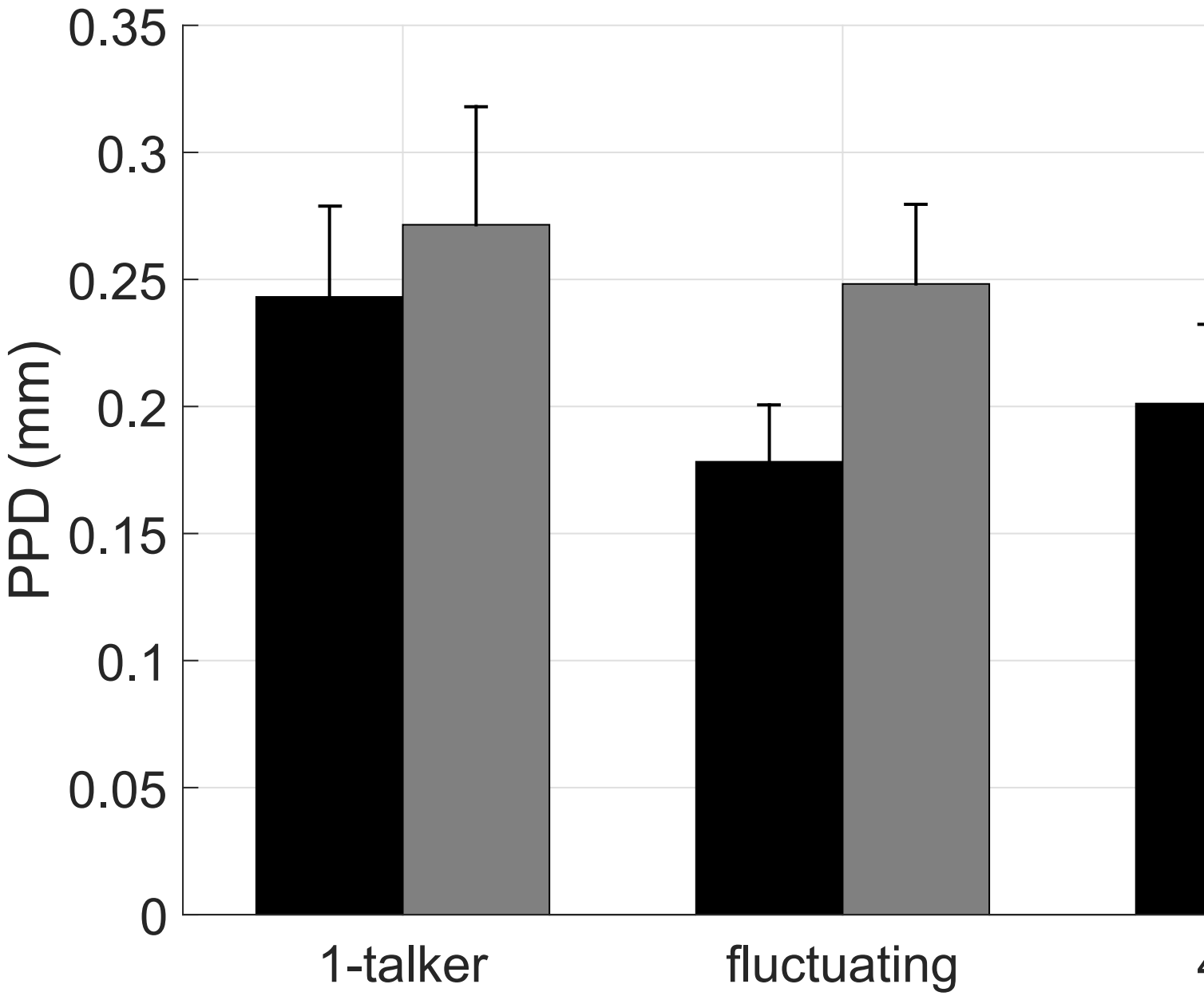
988
989 ** $p < 0.05$; ** $p < 0.01$*

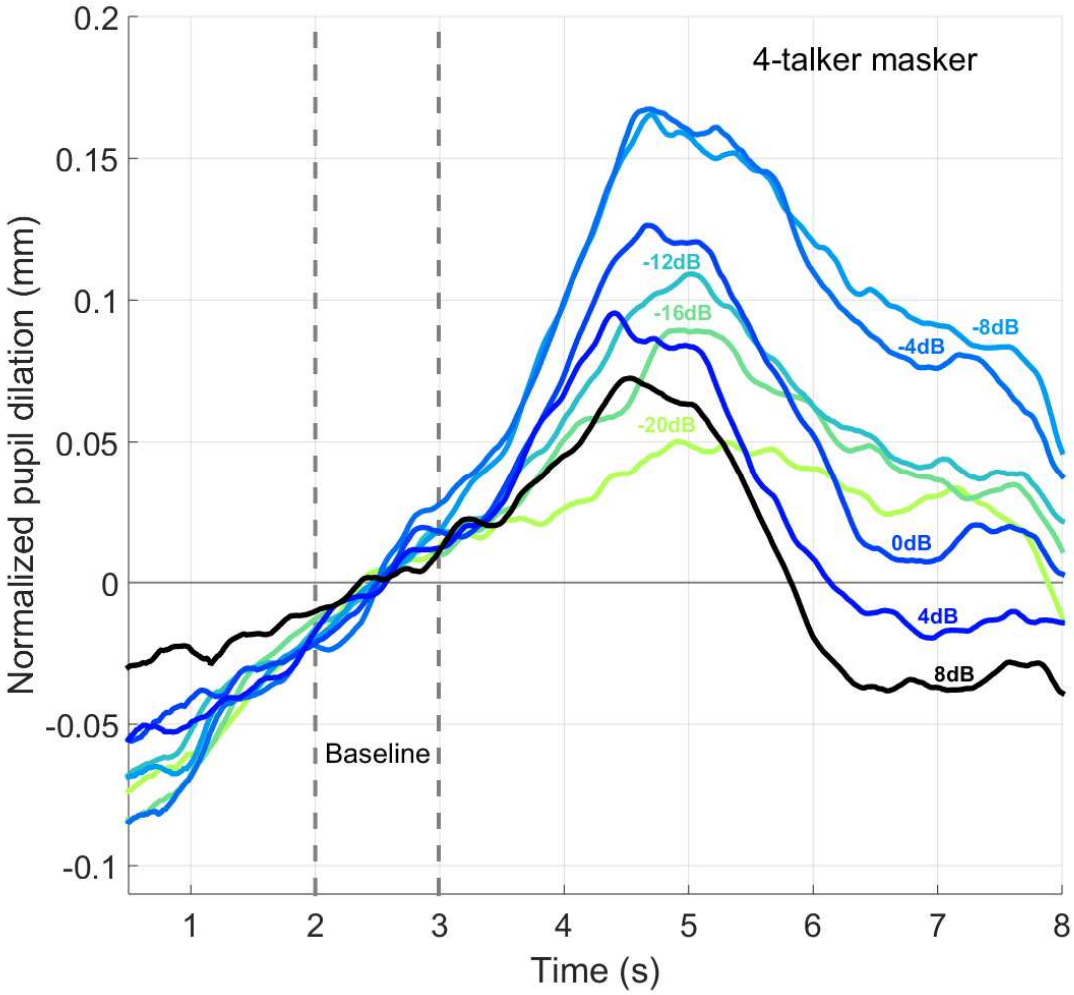


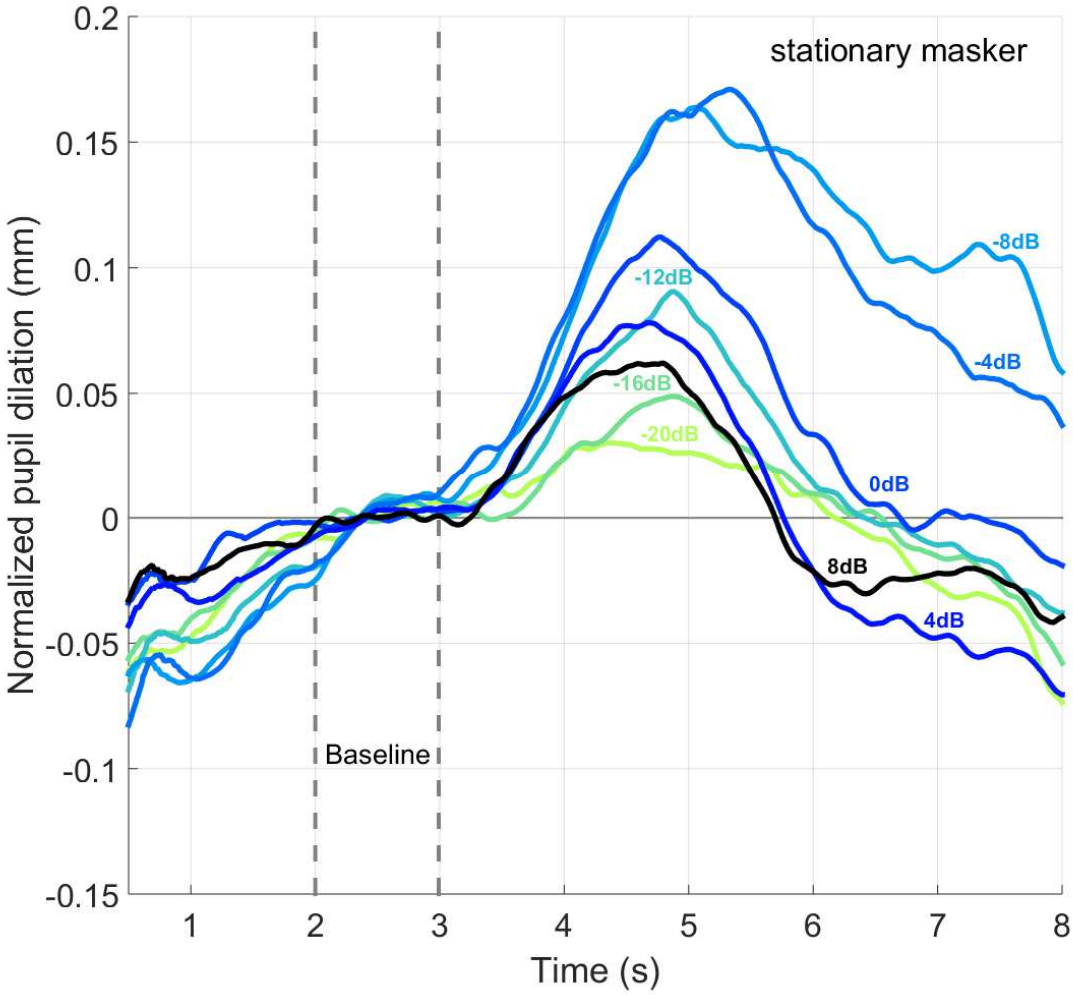


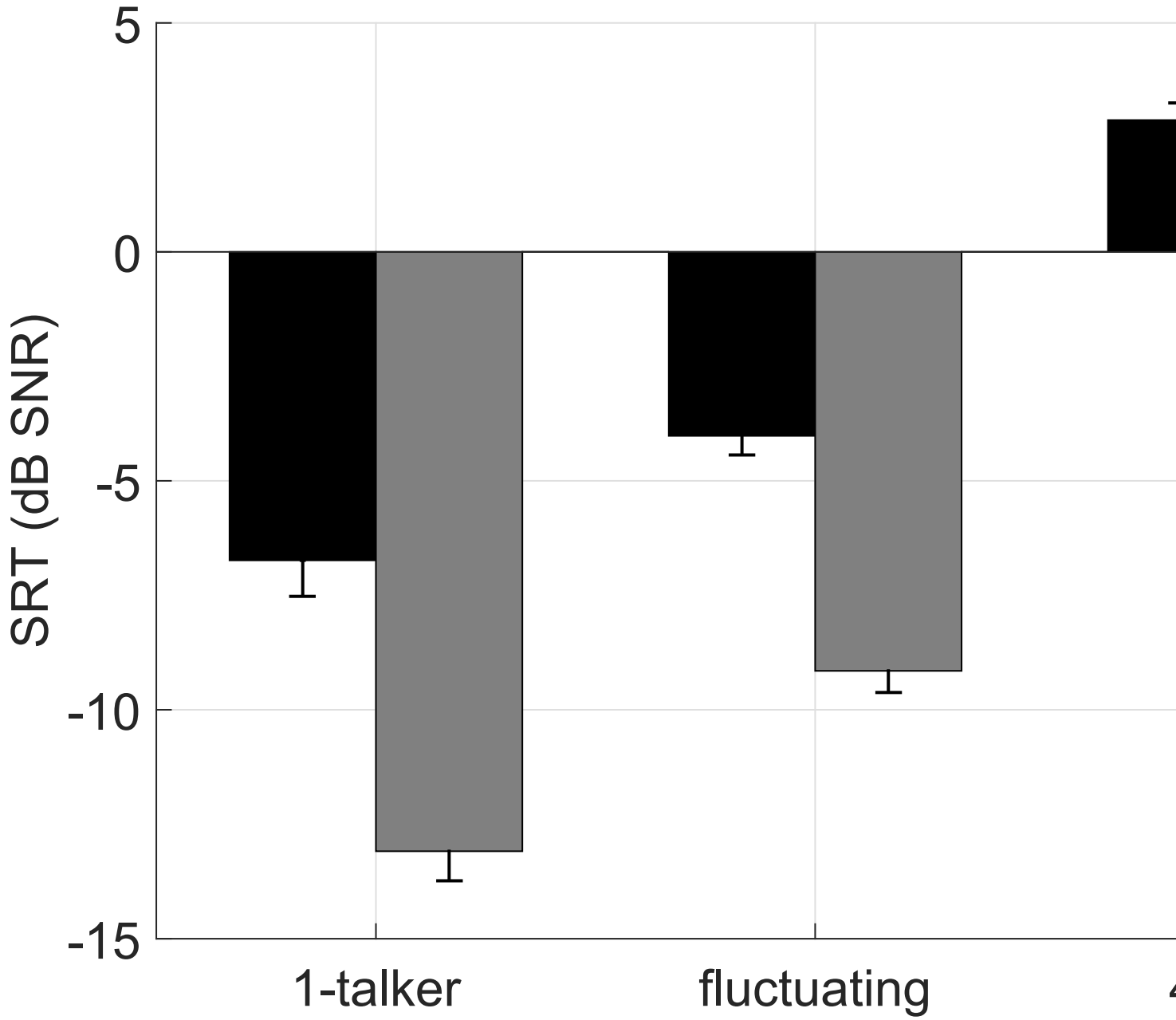

Peak Pupil Dilation (mm)
0.25
0.2
0.15
0.1
0.05
0
-20
-16
-12
-8
-4
Correct recognition (%)
100
50
0
-20
-16
-12
-8
-4
SNR (dB)


Peak Pupil Dilation (mm)
0.25
0.2
0.15
0.1
0.05
0
-20
-16
-12
-8
-4
Correct recognition (%)
100
50
0
-20
-16
-12
-8
-4
SNR (dB)


0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
PPD (mm)
1-talker
fluctuating




stationary masker
-8dB
-12dB
-4dB
-16dB
-20dB
0dB
8dB
4dB
Baseline
Normalized pupil dilation (mm)
Time (s)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
1
2
3
4
5
6
7
8


5
0
-5
-10
-15
SRT (dB SNR)
1-talker
fluctuating

Highlights:

- Two experiments explored the impact of masker type and Signal-to-Noise Ratio on listening effort by means of pupillometry using a speech-in-noise test.
- Listening effort is highly affected by the masker type and the semantic interference of the masker.
- Pupillary response changed non-linearly across a range of fixed SNRs that corresponded to a wide range of recognition performance.
- The pupillary response demonstrated that listening effort is highest at intermediate SNRs corresponding to 30-70% speech intelligibility. Reduced pupillary response was measured at higher (favourable) SNRs corresponding to high intelligibility close to 100 %, reflecting lower listening effort likely due to a favourable listening situation and low task demands. Pupillary response was furthermore reduced at low (unfavourable) SNRs corresponding to intelligibility between 0-30%, which suggested that listeners spent less resources probably due to disengagement and giving up in those adverse listening situations.