Benefit of Higher Maximum Force Output on Listening Effort in Bone-Anchored Hearing System Users: A Pupillometry Study

OBJECTIVES: The aim of this study was to compare listening effort, as estimated via pupillary response, during a speech-in-noise test in bone-anchored hearing system (BAHS) users wearing three different sound processors. The three processors, Ponto Pro (PP), Ponto 3 (P3), and Ponto 3 SuperPower (P3SP), differ in terms of maximum force output (MFO) and MFO algorithm. The hypothesis was that listeners would allocate lower listening effort with the P3SP than with the PP, as a consequence of a higher MFO and, hence, fewer saturation artifacts in the signal.

DESIGN: Pupil dilations were recorded in 21 BAHS users with a conductive or mixed hearing loss, during a speech-in-noise test performed at positive signal-to-noise ratios (SNRs), where the speech and noise levels were individually adjusted to lead to 95% correct intelligibility with the PP. The listeners had to listen to a sentence in noise, retain it for 3 seconds and then repeat it, while an eye-tracking camera recorded their pupil dilation. The three sound processors were tested in random order with a single-blinded experimental design. Two conditions were performed at the same SNR: Condition 1, where the speech level was designed to saturate the PP but not the P3SP, and condition 2, where the overall sound level was decreased relative to condition 1 to reduce saturation artifacts.

RESULTS: The P3SP led to higher speech intelligibility than the PP in both conditions, while the performance with the P3 did not differ from the performance with the PP and the P3SP. Pupil dilations were analyzed in terms of both peak pupil dilation (PPD) and overall pupil dilation via growth curve analysis (GCA). In condition 1, a significantly lower PPD, indicating a decrease in listening effort, was obtained with the P3SP relative to the PP. The PPD obtained with the P3 did not differ from the PPD obtained with the other two sound processors. In condition 2, no difference in PPD was observed across the three processors. The GCA revealed that the overall pupil dilation was significantly lower, in both conditions, with both the P3SP and the P3 relative to the PP, and, in condition 1, also with the P3SP relative to the P3.

CONCLUSIONS: The overall effort to process a moderate to loud speech signal was significantly reduced by using a sound processor with a higher MFO (P3SP and P3), as a consequence of fewer saturation artifacts. These findings suggest that sound processors with a higher MFO may help BAHS users in their everyday listening scenarios, in particular in noisy environments, by improving sound quality and, thus, decreasing the amount of cognitive resources utilized to process incoming speech sounds.
Effect of Speech Rate on Neural Tracking of Speech

Speech comprehension requires effort in demanding listening situations. Selective attention may be required for focusing on a specific talker in a multi-talker environment, may enhance effort by requiring additional cognitive resources, and is known to enhance the neural representation of the attended talker in the listener's neural response. The aim of the study was to investigate the relation of listening effort, as quantified by subjective effort ratings and pupil dilation, and neural speech tracking during sentence recognition. Task demands were varied using sentences with varying levels of linguistic complexity and using two different speech rates in a picture-matching paradigm with 20 normal-hearing listeners. The participant's task was to match the acoustically presented sentence with a picture presented before the acoustic stimulus. Afterwards they rated their perceived effort on a categorical effort scale. During each trial, pupil dilation (as an indicator of listening effort) and electroencephalogram (as an indicator of neural speech tracking) were recorded. Neither measure was significantly affected by linguistic complexity. However, speech rate showed a strong influence on subjectively rated effort, pupil dilation, and neural tracking. The neural tracking analysis revealed a shorter latency for faster sentences, which may reflect a neural adaptation to the rate of the input. No relation was found between neural tracking and listening effort, even though both measures were clearly influenced by speech rate. This is probably due to factors that influence both measures differently. Consequently, the amount of listening effort is not clearly represented in the neural tracking.

The Pupil Dilation Response During Speech Perception in Dark and Light: The Involvement of the Parasympathetic Nervous System in Listening Effort

Recently, the measurement of the pupil dilation response has been applied in many studies to assess listening effort. Meanwhile, the mechanisms underlying this response are still largely unknown. We present the results of a method that separates the influence of the parasympathetic and sympathetic branches of the autonomic nervous system on the pupil response during speech perception. This is achieved by changing the background illumination level. In darkness, the influence of the parasympathetic nervous system on the pupil response is minimal, whereas in light, there is an additional component from the parasympathetic nervous system. Nineteen hearing-impaired and 27 age-matched normal-hearing listeners performed speech reception threshold tests targeting a 50% correct performance level while pupil responses
were recorded. The target speech was masked with a competing talker. The test was conducted twice, once in dark and once in a light condition. Need for Recovery and Checklist Individual Strength questionnaires were acquired as indices of daily-life fatigue. In dark, the peak pupil dilation (PPD) did not differ between the two groups, but in light, the normal-hearing group showed a larger PPD than the hearing-impaired group. Listeners with better hearing acuity showed larger differences in dilation between dark and light. These results indicate a larger effect of parasympathetic inhibition on the pupil dilation response of listeners with better hearing acuity, and a relatively high parasympathetic activity in those with worse hearing. Previously observed differences in PPD between normal and impaired listeners are probably not solely because of differences in listening effort.

Best Practices and Advice for Using Pupillometry to Measure Listening Effort: An Introduction for Those Who Want to Get Started
Within the field of hearing science, pupillometry is a widely used method for quantifying listening effort. Its use in research is growing exponentially, and many labs are (considering) applying pupillometry for the first time. Hence, there is a growing need for a methods paper on pupillometry covering topics spanning from experiment logistics and timing to data cleaning and what parameters to analyze. This article contains the basic information and considerations needed to plan, set up, and interpret a pupillometry experiment, as well as commentary about how to interpret the response. Included are practicalities like minimal system requirements for recording a pupil response and specifications for peripheral, equipment, experiment logistics and constraints, and different kinds of data processing. Additional details include participant inclusion and exclusion criteria and some methodological considerations that might not be necessary in other auditory experiments. We discuss what data should be recorded and how to monitor the data quality during recording in order to minimize artifacts. Data processing and analysis are considered as well. Finally, we share insights from the collective experience of the authors and discuss some of the challenges that still lie ahead.
Impact of SNR, masker type and noise reduction processing on sentence recognition performance and listening effort as indicated by the pupil dilation response

Recent studies have shown that activating the noise reduction scheme in hearing aids results in a smaller peak pupil dilation (PPD), indicating reduced listening effort, at 50% and 95% correct sentence recognition with a 4-talker masker. The objective of this study was to measure the effect of the noise reduction scheme (on or off) on PPD and sentence recognition across a wide range of signal-to-noise ratios (SNRs) from +16 dB to -12 dB and two masker types (4-talker and stationary noise). Relatively low PPDs were observed at very low (-12 dB) and very high (+16 dB to +8 dB) SNRs presumably due to ‘giving up’ and ‘easy listening’, respectively. The maximum PPD was observed with SNRs at approximately 50% correct sentence recognition. Sentence recognition with both masker types was significantly improved by the noise reduction scheme, which corresponds to the shift in performance from SNR function at approximately 5 dB toward a lower SNR. This intelligibility effect was accompanied by a corresponding effect on the PPD, shifting the peak by approximately 4 dB toward a lower SNR. In addition, with the 4-talker masker, when the noise reduction scheme was active, the PPD was smaller overall than that when the scheme was inactive. We conclude that with the 4-talker masker, noise reduction scheme processing provides a listening effort benefit in addition to any effect associated with improved intelligibility. Thus, the effect of the noise reduction scheme on listening effort incorporates more than can be explained by intelligibility alone, emphasizing the potential importance of measuring listening effort in addition to traditional speech reception measures.

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Measuring the Impact of Tinnitus on Aided Listening Effort Using Pupillary Response

Tinnitus can have serious impact on a person's life and is a common auditory symptom that is especially comorbid with hearing loss. This study investigated processing effort required for speech recognition in a group of hearing-impaired people with tinnitus and a control group (CG) of hearing-impaired people without tinnitus by means of pupillary response. Furthermore, the relationship between the pupillary response, self-rating measures of tinnitus severity, and fatigue was examined. Participants performed a speech-in-noise task with a competing four-talker babble at two speech intelligibility levels (50% and 95%) with either an active or inactive noise-reduction scheme while the pupillary response was recorded. Tinnitus participants showed significantly smaller time-dependent pupil dilations and significantly higher fatigue ratings. No correlation was found for the tinnitus severity and pupillary response, but a significant correlation was found between the tinnitus severity and fatigue. As participants with tinnitus generally reported higher fatigue and showed smaller task-evoked pupil dilations, it was speculated that this may suggest an increased activity of the parasympathetic nervous system, which governs the bodily response during rest. The finding that tinnitus participants showed higher fatigue has clinical implications, highlighting the importance of taking steps to decrease the risk of developing long-term fatigue. Finally, the tinnitus participants showed reduced pupillary responses when noise reduction was activated, suggesting a reduced effort from hearing aid signal processing.

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Pupil light reflex evoked by light-emitting diode and computer screen: Methodology and association with need for recovery in daily life

ObjectivesPupil light reflex (PLR) has been widely used as a method for evaluating parasympathetic activity. The first aim of the present study is to develop a PLR measurement using a computer screen set-up and compare its results with the PLR generated by a more conventional setup using light-emitting diode (LED). The parasympathetic nervous system, which is known to control the 'rest and digest' response of the human body, is considered to be associated with daily life fatigue. However, only few studies have attempted to test the relationship between self-reported daily fatigue and physiological measurement of the parasympathetic nervous system. Therefore, the second aim of this study was to investigate the relationship between daily-life fatigue, assessed using the Need for Recovery scale, and parasympathetic activity, as indicated by the PLR parameters. DesignA pilot study was conducted first to develop a PLR measurement set-up using a computer screen. PLRs evoked by light stimuli with different characteristics were recorded to confirm the influence of light intensity, flash duration, and color on the PLRs evoked by the system. In the subsequent experimental study, we recorded the PLR of 25 adult participants to light flashes generated by the screen set-up as well as by a conventional LED set-up. PLR parameters relating to parasympathetic and sympathetic activity were calculated from the
pupil responses. We tested the split-half reliability across two consecutive blocks of trials, and the relationships between the parameters of PLRs evoked by the two set-ups. Participants rated their need for recovery prior to the PLR recordings.

Results
PLR parameters acquired in the screen and LED set-ups showed good reliability for amplitude related parameters. The PLRs evoked by both set-ups were consistent, but showed systematic differences in absolute values of all parameters. Additionally, higher need for recovery was associated with faster and larger constriction of the PLR.

Conclusions
This study assessed the PLR generated by a computer screen and the PLR generated by a LED. The good reliability within set-ups and the consistency between the PLRs evoked by the set-ups indicate that both systems provides a valid way to evoke the PLR. A higher need for recovery was associated with faster and larger constricting PLRs, suggesting increased levels of parasympathetic nervous system activity in people experiencing higher levels of need for recovery on a daily basis.

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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
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; Nielsen and Dau, 2011). The first experiment aimed to replicate and extend earlier observed effects of noise type and semantic interference on listening effort (Koelewijn et al., 2012a). 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 intelligibility 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.

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Speech perception in adverse listening situations can be exhausting. Hearing loss particularly affects processing demands, which requires increased processing effort for successful speech perception in background noise. Signal processing in hearing aids and noise reduction (NR) schemes aim to counteract the effect of noise and reduce the effort required for speech recognition in adverse listening situations. This talk outlines some studies investigating the impact of hearing loss on processing effort and the benefit of a NR scheme on speech recognition and effort. The influence of hearing loss and NR processing on effort was evaluated by measuring the Peak Pupil Dilation (PPD) of listeners while performing a speech recognition task. Speech recognition performances and PPDs were measured in different listening situations varying in SNR and/or speech intelligibility. A significant interaction effect between SNR and hearing-status on effort was found. Moreover, a benefit of the NR scheme on effort was demonstrated for hearing-impaired listeners at positive SNRs, i.e. for listening situations where speech recognition was at ceiling performance. The results emphasized the relevance of measuring processing effort in situations where the traditional speech reception measures fail due to ceiling effects.
noise ratios corresponding to either the individual 50% correct (L50) or the 95% correct (L95) performance level in a 4-talker babble condition with and without the use of a NR scheme. In experiment 1, the PPD differed in response to both changes in the speech intelligibility level (L50 versus L95) and NR scheme. The PPD increased with decreasing intelligibility, indicating higher processing effort under the L50 condition compared with the L95 condition. Moreover, the PPD decreased when the NR scheme was applied, suggesting that the processing effort was reduced. In experiment 2, 2 hearing aids using different NR schemes (fast-acting and slow-acting) were compared. Processing effort changed as indicated by the PPD depending on the hearing aids and therefore on the NR scheme. Larger PPDs were measured for the slow-acting NR scheme. The benefit of applying an NR scheme was demonstrated for both L50 and L95, that is, a situation at which the performance level was at a ceiling. This opens the opportunity for new means of evaluating hearing aids in situations in which traditional speech reception measures are shown not to be sensitive. This is an open access article distributed under the Creative Commons Attribution License 4.0 (CCBY), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

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Impact of Noise and Noise Reduction on Processing effort

The pupil dilation response reflecting cognitive processing effort has been shown to be sensitive to changes in signal-to-noise ratio (SNR) and masker type during sentence recognition in background noise. Our recent research showed that hearing-impaired listeners appear to benefit from a ‘multi-channel enhancement’ (MCE) algorithm in hearing aids, as smaller pupil responses were shown at 50% and 95% correct sentence recognition performance in a 4-talker babble masker for active versus inactive MCE processing. The objective of this study was to measure the effect of MCE on the pupil dilation response and on speech recognition across a wide range of SNRs for two masker types. For 24 hearing-impaired listeners, the pupil dilation response was recorded during sentence recognition, in a design with 8 SNRs x 2 masker types (4-talker babble vs. stationary noise) x 2 algorithm modes (MCE active vs. inactive). Based on our recent research we hypothesized an inverse u-shaped function of the pupil response across SNRs with relatively small pupil dilations at very low and very high SNRs. In the mid-range of SNRs, we expected improved sentence recognition and decreased cognitive processing effort for active MCE compared to inactive MCE. We will present the results of this experiment.

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Impact of stimulus-related factors and hearing impairment on listening effort as indicated by pupil dilation

Previous research has reported effects of masker type and signal-to-noise ratio (SNR) on listening effort, as indicated by the peak pupil dilation (PPD) relative to baseline during speech recognition. At about 50% correct sentence recognition performance, increasing SNRs generally results in declining PPDs, indicating reduced effort. However, the decline in PPD over SNRs has been observed to be less pronounced for hearing-impaired (HI) compared to normal-hearing (NH) listeners. The presence of a competing talker during speech recognition generally resulted in larger PPDs as compared to the presence of a fluctuating or stationary background noise. The aim of the present study was to examine the interplay between hearing-status, a broad range of SNRs corresponding to sentence recognition performance varying from 0 to 100% correct, and different masker types (stationary noise and single-talker masker) on the PPD during speech perception. Twenty-five HI and 32 age-matched NH participants listened to sentences across a broad range of SNRs, masked with speech from a single talker (-25 dB to +15 dB SNR) or with stationary noise (-12 dB to +16 dB). Correct sentence recognition scores and pupil responses were recorded during stimulus presentation. With a stationary masker, NH listeners show maximum PPD across a relatively narrow range of low SNRs, while HI listeners show relatively large PPD across a wide range of ecological SNRs. With the single-talker masker, maximum PPD was observed in the mid-range of SNRs around 50% correct sentence recognition performance, while smaller PPDs were observed at lower and higher SNRs. Mixed-model ANOVAs revealed significant interactions between hearing-status and SNR on the PPD for both masker types. Our data show a different pattern of PPDs across SNRs between groups, which indicates that listening and the allocation of effort during listening in daily life environments may be different for NH and HI listeners.

Impact of tinnitus, noise and noise reduction on processing effort: a pupillometry study

Hearing loss affects processing effort, potentially making speech perception in noise exhausting. To achieve successful speech understanding, people with hearing impairment need to increase their effort, particularly in listening conditions with low signal-to-noise ratios (SNRs). Research with pupillometry indicated a benefit of noise reduction algorithms for people with hearing-impairment, where a decreased peak pupil dilation (PPD) reflected a reduced effort. Tinnitus may increase the processing effort further due to the perception of an extra sound stimulus and a general effect of the tinnitus on quality of life. The present study aims to investigate the effect of tinnitus on processing effort while performing a speech recognition task as indicated by the PPD response. Another objective is to examine the benefit of a noise reduction (NR) scheme on effort. For a group of hearing-impaired listeners with tinnitus and a control group of hearing-impaired participants without tinnitus, the PPD response was recorded during sentence recognition, in a design with 2 SNRs (corresponding to the individual 50% and the individual 95% intelligibility level) x 2 algorithm modes (NR active vs. inactive). Furthermore, questionnaires are applied to evaluate perceived fatigue and tinnitus. It is expected that hearing-
impaired participants with tinnitus will have an increased PPD compared to control participants. Since tinnitus has been found to have a larger impact in quiet surroundings, it is hypothesized that the tinnitus participants will have less benefit of the NR scheme in the condition corresponding to the individual 95% speech intelligibility level. Ultimately, it is also hypothesized that more severe subjective ratings of tinnitus and fatigue will correlate with increased processing effort in the speech recognition task. The results of the study will be presented and discussed.

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Relations Between Self-Reported Daily-Life Fatigue, Hearing Status, and Pupil Dilation During a Speech Perception in Noise Task
People with hearing impairment are likely to experience higher levels of fatigue because of effortful listening in daily communication. This hearing-related fatigue might not only constrain their work performance but also result in withdrawal from major social roles. Therefore, it is important to understand the relationships between fatigue, listening effort, and hearing impairment by examining the evidence from both subjective and objective measurements. The aim of the present study was to investigate these relationships by assessing subjectively measured daily-life fatigue (self-report questionnaires) and objectively measured listening effort (pupillometry) in both normally hearing and hearing-impaired participants. Twenty-seven normally hearing and 19 age-matched participants with hearing impairment were included in this study. Two self-report fatigue questionnaires Need For Recovery and Checklist Individual Strength were given to the participants before the test session to evaluate the subjectively measured daily fatigue. Participants were asked to perform a speech reception threshold test with single-talker masker targeting a 50% correct response criterion. The pupil diameter was recorded during the speech processing, and we used peak pupil dilation (PPD) as the main outcome measure of the pupillometry. No correlation was found between subjectively measured fatigue and hearing acuity, nor was a group difference found between the normally hearing and the hearing-impaired participants on the fatigue scores. A significant negative correlation was found between self-reported fatigue and PPD. A similar correlation was also found between Speech Intelligibility Index required for 50% correct and PPD. Multiple regression analysis showed that factors representing “hearing acuity” and “self-reported fatigue” had equal and independent associations with the PPD during the speech in noise test. Less fatigue and better hearing acuity were associated with a larger pupil dilation. To the best of our knowledge, this is the first study to investigate the relationship between a subjective measure of daily-life fatigue and an objective measure of pupil dilation, as an indicator of listening effort. These findings help to provide an empirical link between pupil responses, as observed in the laboratory, and daily-life fatigue. This is an open-access article distributed under the terms of the Creative Commons Attribution-Non Commercial-No Derivatives License 4.0 (CCBY-NC-ND), where it is permissible to download and share the work provided it is properly cited. The work cannot be changed in any way or used commercially without permission from the journal.

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Comparing eye tracking with electrooculography for measuring individual sentence comprehension duration

The aim of this study was to validate a procedure for performing the audio-visual paradigm introduced by Wendt et al. (2015) with reduced practical challenges. The original paradigm records eye fixations using an eye tracker and calculates the duration of sentence comprehension based on a bootstrap procedure. In order to reduce practical challenges, we first reduced the measurement time by evaluating a smaller measurement set with fewer trials. The results of 16 listeners showed effects comparable to those obtained when testing the original full measurement set on a different collective of listeners. Secondly, we introduced electrooculography as an alternative technique for recording eye movements. The correlation between the results of the two recording techniques (eye tracker and electrooculography) was $r = 0.97$, indicating that both methods are suitable for estimating the processing duration of individual participants. Similar changes in processing duration arising from sentence complexity were found using the eye tracker and the electrooculography procedure. Thirdly, the time course of eye fixations was estimated with an alternative procedure, growth curve analysis, which is more commonly used in recent studies analyzing eye tracking data. The results of the growth curve analysis were compared with the results of the bootstrap procedure. Both analysis methods show similar processing durations.
individual differences in the participants’ working memory capacity (WMC). The results showed that the subjectively rated effort was mostly affected by the noise level and less by syntactic complexity. Conversely, pupil dilations increased with syntactic complexity but only showed a small effect of the noise level. Participants with higher WMC showed increased pupil responses in the higher-level noise condition but rated sentence comprehension as being less effortful compared to participants with lower WMC. Overall, the results demonstrate that pupil dilations and subjectively rated effort represent different aspects of effort. Furthermore, the results indicate that effort can vary in situations with high speech intelligibility.

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**Pitch Discrimination In Musicians and Non-Musicians: Effects of Harmonic Resolvability and Processing Effort**
Musicians typically show enhanced pitch discrimination abilities compared to non-musicians. The present study investigated this perceptual enhancement behaviorally and objectively for resolved and unresolved complex tones to clarify whether the enhanced performance in musicians can be ascribed to increased peripheral frequency selectivity and/or to a different processing effort in performing the task. In a first experiment, pitch discrimination thresholds were obtained for harmonic complex tones with fundamental frequencies (F0s) between 100 and 500 Hz, filtered in either a low- or a high-frequency region, leading to variations in the resolvability of audible harmonics. The results showed that pitch discrimination performance in musicians was enhanced for resolved and unresolved complexes to a similar extent. Additionally, the harmonics became resolved at a similar F0 in musicians and non-musicians, suggesting similar peripheral frequency selectivity in the two groups of listeners. In a follow-up experiment, listeners’ pupil dilations were measured as an indicator of the required effort in performing the same pitch discrimination task for conditions of varying resolvability and task difficulty. Pupillometry responses indicated a lower processing effort in the musicians versus the non-musicians, although the processing demand imposed by the pitch discrimination task was individually adjusted according to the behavioral thresholds. Overall, these findings indicate that the enhanced pitch discrimination abilities in musicians are unlikely to be related to higher peripheral frequency selectivity and may suggest an enhanced pitch representation at more central stages of the auditory system in musically trained listeners.

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How Hearing Impairment Affects Sentence Comprehension: Using Eye Fixations to Investigate the Duration of Speech Processing

The main objective of this study was to investigate the extent to which hearing impairment influences the duration of sentence processing. An eye-tracking paradigm is introduced that provides an online measure of how hearing impairment prolongs processing of linguistically complex sentences; this measure uses eye fixations recorded while the participant listens to a sentence. Eye fixations toward a target picture (which matches the aurally presented sentence) were measured in the presence of a competitor picture. Based on the recorded eye fixations, the single target detection amplitude, which reflects the tendency of the participant to fixate the target picture, was used as a metric to estimate the duration of sentence processing. The single target detection amplitude was calculated for sentence structures with different levels of linguistic complexity and for different listening conditions: in quiet and in two different noise conditions. Participants with hearing impairment spent more time processing sentences, even at high levels of speech intelligibility. In
addition, the relationship between the proposed online measure and listener-specific factors, such as hearing aid use and cognitive abilities, was investigated. Longer processing durations were measured for participants with hearing impairment who were not accustomed to using a hearing aid. Moreover, significant correlations were found between sentence processing duration and individual cognitive abilities (such as working memory capacity or susceptibility to interference). These findings are discussed with respect to audiological applications.

Impact of background noise and sentence complexity on cognitive processing demands
Speech comprehension in adverse listening conditions requires cognitive processing demands. Processing demands can increase with acoustically degraded speech but also depend on linguistic aspects of the speech signal, such as syntactic complexity. In the present study, pupil dilations were recorded in 19 normal-hearing participants while processing sentences that were either syntactically simple or complex and presented in either high- or low-level background noise. Furthermore, the participants were asked to rate the subjectively perceived difficulty of sentence comprehension. The results showed that increasing noise levels had a greater impact on the perceived difficulty than sentence complexity. In contrast, the processing of complex sentences resulted in greater and more prolonged pupil dilations. The results suggest that while pupil dilations may correlate with cognitive processing demands, acoustic noise has a greater impact on the subjective perception of difficulty.
Informational interference from a competing talker: a thought-provoking but elusive construct

A competing talker can impair speech processing through both energetic masking and informational, cognitive aspects of masking. We refer to the latter as informational interference. We hypothesized that informational interference depletes processing resources that could otherwise be allocated to recognizing and understanding target speech. Consequently, informational interference should be more pronounced for target sentences with high processing demands (complex syntax) than for sentences with low processing demands (simple syntax). Furthermore, informational interference should be particularly marked when participants’ own processing demands are increased, as with non-native listeners. Using a speeded picture selection task, we assessed native and non-native listeners’ understanding of subject-relative (simple) and object-relative (complex) sentences, played against a competing talker vs. a matched energetic mask, at various signal-to-noise ratios (SNRs). Although object-relative sentences were more demanding than subject-relative sentences, the competing talker did not affect performance more than did energetic mask controls. This pattern was comparable for native and non-native listeners, and across SNRs. Moreover, individual differences in working memory were not related to differences in the speeded-selection task, regardless of the mask. Eye-tracking and pupillometric versions of this experiment also yielded similar results. Thus, contrary to prior research, we found no evidence that a competing talker requires greater processing resources than energetic masking alone. To address this discrepancy, an ongoing study aims to determine whether the semantic content of the competing talker’s utterances modulates attention to the target.

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Investigating the effect of competing talkers on speech processing load as shown by task evoked pupil dilation

In everyday communication situations, we have to listen and attend to one (target) speaker in the presence of one or more (competing) speakers. Segregating speech from competing speech required higher cognitive processing demands. Koelewijn and colleagues reported that the type of masker affects processing load especially when the masker contains semantic-linguistic information. Objective of this study was to investigate the effect of competing speech information on cognitive effort during speech perception indicated by task evoked pupil dilation. In contrast to these previous studies, the effect of masker type on processing load was investigated using Danish sentences.

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Using eye movements for analyzing the influence of linguistic complexity, noise, and hearing loss on sentence processing time

High linguistic complexity can reduce speech intelligibility and can increase cognitive effort. A method for detecting the latter was presented by Wendt et al. (2014) using an eye-tracking (ET) paradigm measuring increased processing time for complex sentences. This study evaluates this method and compares the ET method to electrooculography (EOG). The processing time of sentences with different linguistic complexity was measured in quiet and in modulated noise using ET and EOG simultaneously. Eleven participants with hearing impairment and five participants with normal hearing
participated in the study. Processing times measured using ET and using EOG showed a correlation of 94%. Furthermore, our results confirm the findings of Wendt and colleagues, that more complex sentences show increased processing time. This study evaluated that sentence processing time can be analyzed equally well using ET and EOG. The method reveals characteristic consequences of linguistic complexity and noise on sentence processing time which can be used as an indicator of the cognitive effort during sentence comprehension.

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**Analyzing processing effort during sentence comprehension in quiet and in noise: Evidence from eye-fixations and pupil size**
Eye-fixations can be used to investigate sentence processing and the required effort during sentence comprehension. Wendt and colleagues (Wendt et al., 2014) proposed an eye-tracking paradigm to detect time-consuming aspects during sentence processing. Participants’ eye-fixations were recorded within an audio-visual paradigm to investigate the speed of processing sentences with varying syntactic complexity. Even at high speech intelligibility level, a reduced processing speed was measured indicating increased processing effort for complex sentences. Another measure of cognitive processing effort is served by task-evoked pupillary response. For instance, Piquard et al. (2010) showed significantly larger pupil sizes during speech comprehension for syntactically more complex object-relative sentences than for the syntactically less complex subject-relative sentence structures. Here, we compare both methods, i.e. processing speed and pupil size, as indicators for the required effort when processing sentences that differ in their level of syntactic complexity. Furthermore, an interaction of background noise and syntactic complexity is examined by analyzing processing effort for sentences presented in quiet and in noise. Moreover, it is investigated whether both measures provide similar or complementary information about sentence processing and the required effort.

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**An Eye-Tracking Paradigm for Analyzing the Processing Time of Sentences with Different Linguistic Complexities**
An eye-tracking paradigm was developed for use in audiology in order to enable online analysis of the speech comprehension process. This paradigm should be useful in assessing impediments in speech processing. In this paradigm, two scenes, a target picture and a competitor picture, were presented simultaneously with an aurally presented sentence that corresponded to the target picture. At the same time, eye fixations were recorded using an eye-tracking device. The effect of linguistic complexity on language processing time was assessed from eye fixation information by systematically varying linguistic complexity. This was achieved with a sentence corpus containing seven German sentence structures. A novel data analysis method computed the average tendency to fixate the target picture as a function of time during sentence processing. This allowed identification of the point in time at which the participant understood the sentence, referred to as the decision moment. Systematic differences in processing time were observed as a function of linguistic complexity. These differences in processing time may be used to assess the efficiency of cognitive processes involved in resolving linguistic complexity. Thus, the proposed method enables a temporal analysis of the speech comprehension process and has potential applications in speech audiology and psychoacoustics.
Native and non-native sentence comprehension in the presence of a competing talker

Objective correlates of pitch salience using pupillometry

Although objective correlates of pitch salience have been investigated in several neuroimaging studies, the results remain controversial. In the present study, a novel approach to objectively estimate pitch salience was used. Pupil dilation was measured as an indicator of the required effort in performing a pitch discrimination task for complex tones of varying pitch salience. It has been shown that cognitive processing demands of the task can be reflected in the pupil response, whereby pupil size dilates when cognitive load increases. The hypothesis was that pupil size would increase with increasing effort in performing the task and thus with decreasing pitch salience. A group of normal-hearing listeners first performed a behavioral pitch-discrimination experiment, where fundamental frequency difference limens (F0 DLs) were measured as a function of F0. In a second experiment, listeners were presented with trials containing two reference complex tones with a fixed F0 and a deviant tone with a larger F0. Six conditions with different salience, defined by both the frequency region and F0, were considered. Pupil size was measured for each condition, while the subjects' task was to detect the deviants by pressing a response button. The expected trend was that pupil size would increase with decreasing salience. Results for musically trained listeners showed the expected trend, whereby pupil size significantly increased with decreasing salience of the stimuli. Non-musically trained listeners showed, however, a smaller pupil size for the least salient condition as compared to a medium salient condition, probably due to a too demanding task.
Projects:

Evaluation of pupillometry as a diagnostic tool
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