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Research Paper

Eye movements of younger and older adults decrease during story listening in background noise

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ABSTRACT

Assessments of listening effort are increasingly relevant to understanding the speech-comprehension difficulties experienced by older adults. Pupillometry is the most common tool to assess listening effort but has limitations. Recent research has shown that eye movements decrease when listening is effortful and proposed indicators of eye movements as alternative measures. However, much of the work was conducted in younger adults in trial-based sentence-listening paradigms during concurrent visual stimulation. The extent to which eye movements index listening effort during continuous speech listening, independently of visual stimuli, and in older adults, is unknown. In the current study, younger and older adults listened to continuous stories with varying degrees of background noise under free and moving-dots viewing conditions. Eye movements decreased (as indexed by fixation duration, gaze dispersion, and saccade rate) with increasing speech masking. The reduction in eye movements did not depend on age group or viewing conditions, indicating that eye movements can be used to assess effects of speech masking in different visual situations and in people of different ages. The pupil size was only sensitive to speech masking early in the experiment. In sum, the current study suggests that eye movements are a potential tool to assess listening effort during continuous speech listening.

1. Introduction

Speech comprehension in the presence of background masking sound requires a listener to invest more cognitively, for example, relying more on attention and memory, which makes listening effortful (Eckert et al., 2016; Herrmann and Johnsrude, 2020a; Peelle, 2018; Pichora-Fuller et al., 2016). Assessing listening effort is increasingly relevant in the study of speech-comprehension challenges in older adulthood, because older listeners may experience listening effort in noisy situations long before they are diagnosed with having a hearing loss (Helfer and Jesse, 2021; Pichora-Fuller and Levitt, 2012). Listening effort may thus be a potentially early diagnostic marker of hearing loss.

The most common objective tool to assess listening effort is pupillometry (van der Wel and van Steenbergen, 2018; Winn et al., 2018; Zekveld et al., 2018). The pupil dilates when listening effort increases due to masking of speech (Cui and Herrmann, 2023; Herrmann and Ryan, 2024; Koelewijn et al., 2018, 2019; Zekveld et al., 2010), degradation of speech (Kılıç et al., 2024; Zekveld Adriana et al., 2023), or linguistic speech-comprehension challenges (Ayasse and Wingfield, 2018; Kadem et al., 2020; Wendt et al., 2016). However, measuring the pupil also has limitations because its size is sensitive to changes in light (Knapen et al., 2016; Suzuki et al., 2019; Thurman et al., 2021) and the angle of the eye relative to the eye-tracking camera, among other factors (Brisson et al., 2013; Fink et al., 2024; Hayes and Petrov, 2016). To account for the latter, participants are typically instructed to fixate on a point on a computer screen (Farahani et al., 2020; Ohlenforst et al., 2017; Winn and Teece, 2021; Zekveld et al., 2018), but this might reduce external validity because it can reduce memory and mental imagery (Johansson et al., 2012) and reduce behavioral effects of speech comprehension (Cui and Herrmann, 2023). Further, pupillometry is most commonly used in trial-by-trial sentence-listening paradigms (Ayasse and Wingfield, 2018; Borghini and Hazan, 2018; Kadem et al., 2020; Wendt et al., 2016; Winn and Teece, 2021; Winn et al., 2015; Zekveld et al., 2010, 2019), whereas an increasing number of works leverage continuous story-listening paradigms to mitigate the less naturalistic nature of short, disconnected sentences (Brodbeck and

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Simon, 2020; Broderick et al., 2018; Ding and Simon, 2014; Lalor and Foxe, 2010; Panela et al., 2024). The extent to which pupillometry is sensitive to listening challenges under such continuous conditions is a topic of increasing interest (Cui and Herrmann, 2023; Fiedler et al., 2021; Seifi Ala et al., 2020; Widmann et al., 2025; Zhao et al., 2019).

A recent line of studies suggests that eye movements may provide an alternative objective measure to assess challenges during listening. Eye movements decrease when listening becomes difficult, for example, due to background noise that masks speech (Contadini-Wright et al., 2023; Cui and Herrmann, 2023; He et al., 2024; Herrmann and Ryan, 2024). Eye movements also decrease during periods of high compared to low memory load (Dalmaso et al., 2017; Kosch et al., 2018; Walter and Bex, 2021) and due to visual-task difficulty (Nakayama et al., 2002), suggesting domain-general reductions in eye movements under high cognitive load. This suggests that eye-movement systems in cortical and subcortical brain structures are sensitive to task challenges, possibly to reduce the impact of distracting visual information.

Eye movements appear to be sensitive to speech masking even during continuous story listening (Cui and Herrmann, 2023). However, in many of the previous works, including the study using continuous story listening (Cui and Herrmann, 2023), some visual stimulus was presented on the computer screen (e.g., fixation point, one moving dot, several moving dots). This visual dot stimulation was used to increase the likelihood of eye movements, allowing for a better investigation of their reduction due to speech masking (Cui and Herrmann, 2023; Herrmann and Ryan, 2024). It is thus unclear whether visual stimulation is advantageous for assessments of listening challenges through eye movements or whether free viewing on a blank screen is as effective. Finally, the relationship between eye movements and effortful listening has thus far mainly been investigated in younger, normal-hearing adults (Contadini-Wright et al., 2023; Cui and Herrmann, 2023). In a recent sentence-listening study, eye movements were also sensitive to increased speech masking in older adults (Herrmann and Ryan, 2024), but whether this generalizes to continuous story listening is unclear.

In the current study, younger and older adults listened to continuous stories masked by background babble at different signal-to-noise ratios (SNRs) either while a blank screen or a moving-dots display was presented. The aim was to investigate whether pupil size and eye movements are sensitive to speech masking (as a manipulation that induces listening effort) during naturalistic speech listening, and whether the sensitivity to speech masking differs between viewing conditions and/or age groups.

2. Methods and materials

2.1. Participants

Thirty-five younger adults (median age: 23 years, age range: 18–33 years; 16 male, 18 female, 1 non-binary) and thirty-one older adults (median age: 69 years, age range: 55–80 years; 12 male, 19 female) participated in the current study. Participants were native English speakers or learned English before the age of 5 years. They reported having normal hearing and none wore or were prescribed hearing aids. Participants gave written informed consent prior to the experiment and were paid $7.5 CAD per half-hour for their participation. The study was conducted in accordance with the Declaration of Helsinki, the Canadian Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans (TCPS2–2014), and was approved by the Research Ethics Board of the Rotman Research Institute at Baycrest Academy. Data from four additional participants were not analyzed, because recordings in half ($N = 3$) or all ($N = 1$) of the experimental blocks failed due to technical problems.

2.2. Hearing assessment

All experimental procedures were conducted within a sound booth. Pure-tone audiometric thresholds were obtained for 0.25 to 8 kHz using a Maico M28 audiometer. The pure-tone average threshold (PTA) was calculated as the mean threshold across 0.5, 1, 2, and 4 kHz frequencies (Humes, 2019; Stevens et al., 2013). Audiometry was not recorded for two younger and two older participants (administration was simply missed during the recording session). An independent-samples *t*-test was used to analyze age-group differences in the pure-tone average threshold.

All participants self-reported having normal hearing, but some showed clinically relevant hearing loss (PTA > 20 dB HL; Humes, 2019; WHO, 2024; Stevens et al., 2013; see below). All data were included in the analysis, because the sample is representative of community-dwelling adults (Herrmann et al., 2018, 2023; Moore, 2007; Plack, 2014; Presacco et al., 2016) and the current study aimed to investigate more generally whether eye movements are indicative of listening challenges during story listening in younger and older adults. Correlations of eye-movement metrics with PTA assessed the effects of hearing loss as described below.

2.3. Stimulus materials and procedure

Participants listened to four approximately 7.5 min stories from the storytelling podcast The Moth (https://themoth.org/; “Model Magic” by Isobel Connelly [7:30 min]; “Going the Extra Mile” by Luanne Sims [7:36 min]; “The Scare Dee Cats” by Michael Donovan [7:18 min]; “The Long Way Home” by Tod Kelly [7:45 min]). The Moth is a podcast where people tell stories about interesting life events. Stories are highly enjoyable and absorbing (Cui and Herrmann, 2023; Herrmann and Johnsrude, 2020b; Irsik et al., 2022b). Each participant listened to two stories while a blank gray screen was presented, whereas they listened to the other two stories while 16 white dots moved randomly on the screen, as described in detail previously (Cui and Herrmann, 2023; Herrmann and Ryan, 2024), mirroring the stimulation of multiple object tracking paradigms. (Alvarez and Franconeri, 2007; Cavanagh and Alvarez, 2005; Herrmann and Johnsrude, 2018b, B. a; Scholl, 2009). The moving-dots display aimed to facilitate eye movements (see Cui and Herrmann, 2023), but no task was required to avoid a dual-task procedure. Participants were instructed to look at the screen in whatever way they wanted (Herrmann and Ryan, 2024; Johansson et al., 2006, 2011, 2012). The viewing conditions were blocked such that both stories of the same viewing condition were presented in direct succession (starting condition was counterbalanced across participants). The assignment of stories to the viewing conditions and the order in which stories were presented was counterbalanced across participants.

Each story was masked by 12-talker background babble (Bilger, 1984; Wilson et al., 2012). The SNR between the speech signal and the 12-talker babble changed every 27 s to one of five SNR levels (+17, +12, +7, +2, −3 dB SNR; for a similar approach see Irsik et al., 2022b, a; Cui and Herrmann, 2023), corresponding to about a range of 95 % to 55 % of intelligible words in younger adults (Irsik et al., 2022b). Each SNR was manipulated by adjusting the dB level of both the story and the masker. This ensured that the overall sound level remained constant across SNRs and throughout a story, and that the overall level was similar for all stories. Each story started and ended with the +17-dB SNR level to enable participants to clearly hear the beginning and end of the story (these were excluded from the analysis, see below). Each SNR level was presented 3 times in a story, with the exception of the +17 dB SNR level, which was presented 5 times (3 times + beginning and end). The SNR transitioned smoothly from one level to the other over a duration of 1 s. The order of SNR levels was randomized such that a particular SNR could not be heard twice in succession, and that SNR would maximally change by two levels. For each participant, SNR levels were randomized uniquely.

The four stories were presented in four separate blocks, and participants took a break between blocks (median: 5 min; mean: 6 min; range: 2–25 min). Each story was presented continuously for the ~7.5 min duration without any silence periods or interruptions (SNR levels seamlessly transitioned; Cui and Herrmann, 2023; Irsik et al., 2022b, V. C. a). The naturalistic story-listening paradigm thus did not contain any silent or non-speech baseline periods nor unique disconnected trials. After a story ended, participants answered ten comprehension questions about the story. For each comprehension question, participants were asked to select the correct answer out of four multiple choice options.

Prior to the main experiment procedures, participants underwent a familiarization block in which they listened to a short 1:12 min story.

2.4. Experimental setup

Sounds were presented via Sony Dynamic Stereo MDR-7506 headphones and a Steinberg UR22 mkII (Steinberg Media Technologies) external sound card. Experimental procedures were run using Psychtoolbox (v3.0.14) in MATLAB (MathWorks Inc.) on a Lenovo T450s laptop with Microsoft Windows 7. The laptop screen was mirrored to a ViewSonic monitor with a refresh rate of 60 Hz. All sounds were presented at a comfortable listening level that was fixed across participants (~70–75 dB SPL).

2.5. Behavioral data analysis

The proportion of correct responses was calculated for the story comprehension task, separately for each story. The proportion of correct responses were averaged across the two stories for each viewing condition (blank screen, moving-dots display). A repeated measures analysis of variance (rmANOVA) was calculated with the within-participants factor Viewing Condition (blank, dots) and the between-participants factor Age Group (younger, older). Please note that SNR could not be included as a factor in the rmANOVA, because story comprehension was assessed after each story, whereas SNR changed every 27 s within a story. Story comprehension accuracy thus reflects an overall comprehension, unrelated to specific SNR levels, mainly to ensure that participants attend to the story.

2.6. Pupillometry and eye-movement recordings

During the experiments, participants placed their head on a chin and forehead rest facing the computer monitor at a distance of about 70 cm. Pupil size (measured as pupil area) and eye movements were recorded continuously from the right eye (or the left eye if the right eye could not be tracked accurately) using an integrated infrared camera (EyeLink 1000 eye tracker; SR Research Ltd.) at a sampling rate of 500 Hz (centroid tracking mode). Nine-point fixation was used for eye-tracker calibration prior to each block (McIntire et al., 2014).

2.7. Processing of pupil-size and eye-movement data

The main metrics of the current study were pupil size, fixation duration, gaze dispersion, and (micro-) saccade rate (Cui and Herrmann, 2023; Herrmann and Ryan, 2024). Fixation duration and gaze dispersion are broad measures of eye movements that we recently used to non-specifically capture any eye movement changes associated with listening effort (Cui and Herrmann, 2023; Herrmann and Ryan, 2024). A broad measure of eye movements may be particularly advantageous if an index of listening effort is the focus rather than understanding underlying mechanisms. Nevertheless, we also analyzed (micro-) saccade rate (Engbert and Kliegl, 2003; Engbert, 2006; Widmann et al., 2014) since it can be sensitive to memory load and listening effort in trial-based tasks (Contadini-Wright et al., 2023; Dalmaso et al., 2017; Kadosh et al., 2024), although this is not always found (Kadem et al., 2020; Cui and Herrmann, 2023). Henceforth, we refer to this measure simply as saccade rate, acknowledging the fact that micro-saccades and saccades likely share functional characteristics (Martinez-Conde et al., 2009, 2013; Otero-Millan et al., 2008).

Preprocessing was calculated for each experimental block separately using MATLAB. For each eye blink indicated by the eye tracker, all data points of the pupil-size time course and the x and y eye-coordinate time courses between 100 ms before and 200 ms after a blink were set to NaN ('not a number' in MATLAB). Moreover, pupil-size values that differed from the mean pupil size (across a block) by more than 3 times the standard deviation were classified as outliers and the corresponding data points of the pupil-size time course and the x and y eye-coordinate time courses were set to NaN. MATLAB's 'pchip' method was used to interpolate NaN-coded samples in the pupil data. Pupil-size time courses were filtered with a 5-Hz low-pass filter (FIR, 51 points, Kaiser window, $\beta = 4$). X and y eye-coordinate time courses were not interpolated. That is, missing data points (NaNs) were ignored in the calculation of the eye-movement metrics.

Broad changes in eye movements were investigated using fixation duration and gaze dispersion, similar to our previous work (Cui and Herrmann, 2023; Herrmann and Ryan, 2024). Both measure the general tendency for the eyes to move around. Fixation duration was calculated as the time a person's x-y eye coordinates remained in a given location (within 0.5° visual angle; radius of 10 px). For each time point, the corresponding x-y coordinate defined the center of the critical 0.5° visual-angle location. The number of continuous pre- and post-samples was calculated for which the x-y-eye coordinates remained in the defined location. The sample number was divided by the sampling frequency to obtain the fixation duration for the specific time point. If a data value of any pre- or post-sample within the 0.5° visual angle location had been coded NaN (i.e., was missing), the fixation duration of the corresponding time point was set to NaN and ignored during averaging.

Gaze dispersion was calculated as the standard deviation in gaze across time points, averaged across x- and y-coordinates, and transformed to logarithmic values to make the metric's distributional properties more Gaussian. Smaller values indicate less gaze dispersion. To obtain time courses for gaze dispersion, it was calculated for 1-s sliding time windows centered sequentially on each time point. If more than 90 % of data were unavailable within a 1-s time window (that is, 450 or more samples were NaN-coded), gaze dispersion for the corresponding time point was set to NaN and ignored during averaging (Cui and Herrmann, 2023; Herrmann and Ryan, 2024).

Saccade rate was calculated as a more specific measure of eye movements. Saccades/ microsaccades were identified using a method that computes thresholds based on velocity statistics from x- and y-coordinate trial time courses and then identifies saccades/microsaccades as events passing that threshold (Engbert and Kliegl, 2003; Engbert, 2006). Similar to gaze dispersion, a 1-s sliding window was sequentially moved across the data of an experimental block. For each 1-s time window, the vertical and horizontal eye movement time series were transformed into velocities, and saccades/mircosaccades were classified as outliers if they exceeded a relative velocity threshold of 15 the standard deviation of the eye-movement velocity and persisted for 6 ms or longer. Previous work differed in the specific velocity threshold that was used, with some work using a velocity threshold of 5 (Engbert and Kliegl, 2003; Widmann et al., 2014), others used a threshold of 15 (Kadem et al., 2020), whereas yet other tested several (Cui and Herrmann, 2023). A threshold of 15 was chosen here, because a threshold of 5 lead to an unrealistically high saccade rate (~10 Hz). If any of the x- or y-values in the eye-tracking time courses comprised an NaN, the saccade rate for this specific sliding window was set to NaN (note that the saccade rate calculation requires continuous data points within the analysis window, prohibiting the presence of NaNs).

2.8. Statistical analysis of pupil size, fixation duration, and gaze dispersion

Pupil size, fixation duration, gaze dispersion, and saccade rate were separately averaged within each 27-s SNR segment of a story. Data from the +17 dB SNR segments at the beginning and end were not used for analysis, because they might otherwise give more weight to this condition in the analysis. For each participant and eye-tracking metric (pupil size, fixation duration, gaze dispersion, saccade rate), this resulted in 15 data points per block, consisting of three times the 5 SNR conditions (+17, +12, +7, +2, −3 dB).

A multi-level regression analysis was performed in MATLAB (Holmes and Friston, 1998; Penny and Holmes, 2007; Lindquist, 2008; Worsley et al., 2002). On the first level, a linear model per eye-tracking metric (i.e., pupil size, fixation duration, gaze dispersion, saccade rate) was fitted separately for each participant. The predictors of interest in the model were SNR (coded: −3, +2, +7, +12, +17 dB, and then zero-centered), Viewing Condition (coded: −0.5, 0.5 for blank and moving dots, respectively), the SNR × Viewing Condition interaction, and an intercept (capturing the overall magnitude). Previous work suggests that modeling time-on-task is important to account for longer term trends in the data (Benwell et al., 2018; Fink et al., 2024; McLaughlin et al., 2023; Unsworth and Robison, 2016; Widmann et al., 2025). Hence, segment number was also included as a linear trend (coded −7 to 7 in increments of 1) and a quadratic trend (squared linear predictor) to account for changes within a block of story listening (i.e., time-on-task). For each participant and eye-tracking metric, the result of the first-level analysis was a coefficient for SNR, Viewing Condition, SNR × Viewing Condition, and the intercept as well as for the linear and quadratic time-on-task trends, describing the relationship with the eye-tracking metric.

On the second level, coefficients were tested against zero using a one-sample *t*-test (except for the intercept), essentially testing the main effects of SNR and Viewing Condition, and the SNR × Viewing Condition interaction. One-sample *t*-tests were also conducted for linear and quadratic time-on-task trends, showing significant effects for all four eye-tracking metrics (for all $t > 2$, $p < 0.05$; except for the quadratic trend for saccade rate $p > 0.1$). Linear and quadratic trends were removed for plotting the data and not further considered (e.g., all predicted values depicted in the figures were computed accounting for linear and quadratic trends by fixing the segment at zero). An independent samples *t*-test on the intercept was calculated to assess the main effect of Age Group. Independent samples *t*-tests on the coefficients for SNR, Viewing Condition, and SNR × Viewing Condition were also calculated to assess interactions with Age Group. Effect sizes are provided as Cohen's d (Cohen, 1988).

In an explorative multi-level regression analysis, we also examined whether an SNR effect on eye metrics may be greater in the beginning of the experimental session. To this end, the regressor for Viewing Condition was replaced by a regressor coding for the block number. The experimental design and available data did not allow running a larger regression model including Viewing Condition and all interactions with Block. Analysis of block-wise effects were calculated post hoc and should be considered exploratory.

Additional analyses were calculated to investigate the relationship between changes in the pupil size and changes in the eye-movement metrics (gaze dispersion, fixation duration, saccade rate). To this end, between-participant partial correlations were calculated separately between the pupil size and the three eye-movement metrics using the linear coefficient for the SNR effect (partialling out age group).

We also investigated the between-participant relationship between pure-tone average threshold (PTA) and eye-tracking metrics (i.e., pupil size, fixation duration, gaze dispersion, saccade rate). To this end, separately for each eye-tracking metric, a regression model was calculated using the estimated linear coefficient for SNR from each participant's linear model as the dependent measure (i.e., the SNR effect) and pure-tone average threshold (PTA) as the predictor. Age group was included as an additional regressor to account for effects of age independent of hearing loss. Additional regressions were calculated to examine whether PTA predicts the overall magnitude of the eye-tracking metrics (using the estimated intercept from each participant's linear model), again including age group as a regressor.

3. Results

Pure-tone average thresholds (PTAs) were greater for older compared to younger adults ($t_{60} = 7.163$, $p = 1.3 \times 10^{-9}$, $d = 1.820$; Figs. 1A and B), as expected based on the known elevated thresholds in community-dwelling older adults (Cruickshanks et al., 1998; Goman and Lin, 2016; Herrmann et al., 2018, 2023; Moore, 2007; Plack, 2014; Presacco et al., 2016). Some older adults had PTAs greater than 20 dB HL, which would be considered clinical hearing loss (Humes, 2019; Stevens et al., 2013; WHO, 2024), but the distribution of PTAs is continuous, suggesting a regression model is appropriate to investigate the impact of hearing function on eye-tracking metrics (see below).

Despite elevated thresholds for older adults, story comprehension did not differ between age groups ($F_{1,64} = 0.087$, $p = 0.769$, $\omega^2 < 0.001$) nor between the two viewing conditions ($F_{1,64} = 0.021$, $p = 0.886$, $\omega^2 < 0.001$). There was also no interaction ($F_{1,64} = 0.447$, $p = 0.506$, $\omega^2 < 0.001$). Performance was high overall (Fig. 1C), indicating participants paid attention to the stories. Since SNR changed every 27 s throughout a story, participants may have been able to use information from easier listening segments to make up for information they may have missed or misheard during more difficult listening segments to answer comprehension questions.

For the analysis of the pupil size, one person's dataset was removed, because their data point for the Viewing Condition effect (estimated coefficient) was over 7 times the standard deviation below the sample mean. Inclusion vs exclusion of this person's data had no qualitative impact – in terms of significance – on any of the other effects; none of the conclusions are affected because of the data removal. Multi-level regression modeling to predict the pupil size revealed no effect of SNR ($t_{64} = -0.322$, $p = 0.749$, $d = 0.040$), and there was no interaction involving SNR (for all $t < 1.9$, $p > 0.05$). The pupil size was greater for the moving-dots display than the blank screen (effect of Viewing Condition: $t_{64} = 6.130$, $p = 6.1 \times 10^{-8}$, $d = 0.760$), and this interacted with Age Group ($t_{63} = 4.297$, $p = 6.1 \times 10^{-5}$, $d = 1.069$). The larger pupil size for the moving-dots display than the blank screen was significant for both age groups (for both $t > 2.1$, $p < 0.04$), but the difference was greater in younger adults. The exploratory analysis to examine differences in the SNR effect across blocks showed a significant SNR × Block interaction ($t_{64} = 2.089$, $p = 0.041$, $d = 0.259$), resulting from an increase in the pupil size as SNR decreased but only in the first block ($t_{64} = -2.105$, $p = 0.039$, $d = 0.261$; no Age Group difference: $p > 0.1$) and not in any of the other three blocks (for all > 0.6). The low sensitivity of the pupil size to SNR is further shown in pupil-size time courses time-locked to the transition from one SNR to the next (Figure S1 in the Supplementary Materials). This analysis shows only a transient SNR effect – with a larger pupil size for difficult than easy SNRs – within the first few seconds after a transition (consistent with previous works using sentence-listening paradigms; Cui and Herrmann, 2023; Kadem et al., 2020Wendt et al., 2017), whereas no SNR effect was observed past this early post-transition effect (Figure S1).

The multi-level regression model shows that fixation duration increased as the SNR decreased (more speech masking; effect of SNR: $t_{65} = -3.194$, $p = 0.002$, $d = 0.393$) and was greater for the blank screen than the moving-dots display (effect of Viewing Condition: $t_{65} = -2.714$, $p = 0.009$, $d = 0.334$; Fig. 3). Older adults moved their eyes overall more than younger adults (effect of Age Group: $t_{64} = 3.576$, $p = 6.7 \times 10^{-4}$, $d = 0.882$). There were no interactions (for all $t < 1.3$, $p > 0.2$). The exploratory analysis did not reveal a difference in the SNR effect between blocks (SNR × Block interaction: $t_{65} = 0.643$, $p = 0.523$, $d = 0.079$; SNR effects for blocks 1–4: $p = 0.004$, $p = 0.036$; $p = 0.141$, $p = 0.148$, respectively).

Gaze dispersion mirrored the results from the fixation duration analysis. Multi-level regression modeling revealed a decrease in gaze dispersion as the SNR decreased (more speech masking; effect of SNR: $t_{65} = 4.821$, $p = 9 \times 10^{-6}$, $d = 0.593$) and gaze dispersion was greater for the moving-dots display than the blank screen (effect of Viewing

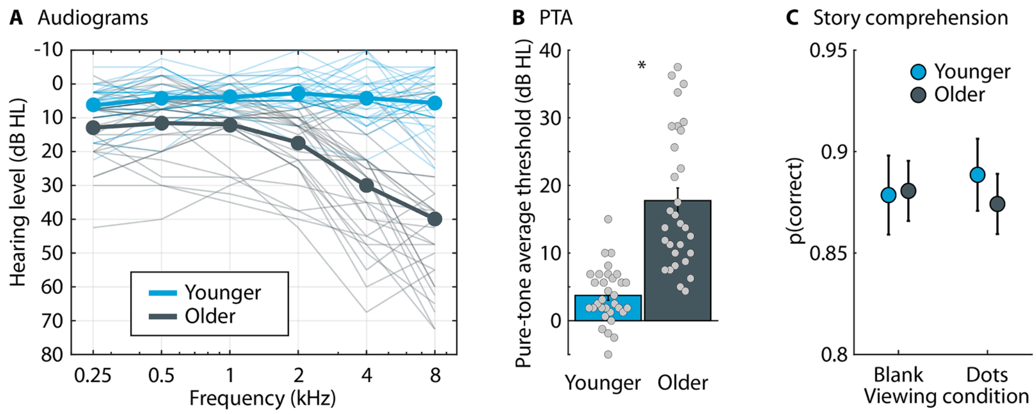

Fig. 1. Audiometric and behavioral measures. A: Audiograms. The thin lines show data of individual participants, whereas the thick lines show the mean across participants. **B:** Pure-tone average thresholds (average across audiometric thresholds at 0.5, 1, 2, 4 kHz). The bar graphs show the mean across participants and individual dots reflect thresholds from individual participants. Error bars reflect the standard error of the mean (SEM). **C:** Mean and SEM for the story-comprehension assessment. $^{*}p < 0.05$.

Condition: $t_{65} = 3.509$, $p = 8.2 \times 10^{-4}$, $d = 0.432$; Fig. 4). Numerically, older adults moved their eyes more than younger adults, but this was not significant for gaze dispersion (effect of Age Group: $t_{64} = 1.602$, $p = 0.114$, $d = 0.395$). There were no interactions (for all $t < 0.8$, $p > 0.4$). The exploratory analysis did not reveal any difference in the SNR effect across blocks (SNR × Block interaction: $t_{65} = 1.061$, $p = 0.293$, $d = 0.131$; SNR effects for blocks 1–4: $p < 0.001$, $p = 0.005$; $p < 0.001$, $p = 0.005$, respectively).

The analysis of saccade rate also showed comparable results. Participants made fewer saccades/microsaccades as the SNR decreased (more speech masking; effect of SNR: $t_{65} = 3.825$, $p = 3 \times 10^{-4}$, $d = 0.471$) and for the blank screen than the moving-dots display (effect of Viewing Condition: $t_{65} = 5.236$, $p = 1.9 \times 10^{-6}$, $d = 0.645$; Fig. 5). The saccade rate was overall greater for older than younger adults (effect of Age Group: $t_{64} = 3.485$, $p = 8.9 \times 10^{-4}$, $d = 0.86$). There were no interactions (for all $t < 1.1$, $p > 0.25$). The exploratory analysis did not reveal a difference in the SNR effect between blocks (SNR × Block interaction: $t_{65} = 1.119$, $p = 0.267$, $d = 0.138$; SNR effects for blocks 1–4: $p = 0.001$, $p = 0.115$; $p = 0.56$, $p = 0.585$, respectively). Note, however, that the estimation of SNR effects for separate blocks was a bit more poorly (Fig. 5C), because data points for saccade calculations were sparser.

Between-participant correlations between the pupil size and the eye-movement metrics (gaze dispersion, fixation duration, saccade rate) for the linear SNR coefficient revealed no significant relationships (fixation duration: $r = 0.215$, $p = 0.089$; gaze dispersion: $r = –0.049$, $p = 0.700$; saccade rate: $r = –0.117$, $p = 0.358$; partialling out age group). Limiting the between-participant correlations to the SNR effect in the first block of the experiment revealed a significant negative correlation between pupil size and saccade rate ($r = –0.253$, $p = 0.043$), whereas the correlation between pupil size and the other two eye-movement measures were not significant (fixation duration: $r = 0.111$, $p = 0.383$; gaze dispersion: $r = –0.170$, $p = 0.179$). Please note that these correlations are exploratory and should be interpreted with caution.

The SNR effect correlated between the three eye-movement metrics (fixation duration with gaze dispersion: $r = –0.638$, $p = 1.4 \times 10^{-8}$; gaze dispersion with saccade rate: $r = 0.765$, $p = 1.8 \times 10^{-13}$; fixation duration with saccade rate: $r = –0.502$, $p = 2.4 \times 10^{-5}$; partialling out age group).

Finally, regression models were calculated to examine whether the pure-tone average threshold (PTA) predicts SNR-related changes or overall responses of eye-tracking metrics (pupil size, fixation duration, gaze dispersion, saccade rate). For none of the regressions did PTA predict SNR-related changes or overall responses of the eye-tracking metrics (for all $p > 0.05$; also when limited to the 1st block). Older adults moved their eyes more than younger adults as indicated by the significant age-group intercept effects for fixation duration, gaze dispersion, and saccade rate (fixation duration: $t_{61} = -2.310$, $p = 0.024$; gaze dispersion: $t_{61} = 2.009$, $p = 0.049$; saccade rate: $t_{61} = 2.509$, $p = 0.015$; pupil size showed a marginally significant reduction in older adults: $t_{60} = -1.971$, $p = 0.053$), which is consistent with the analyses reported above. There were no age-group effects for the SNR-related changes in eye-tracking metrics (for all $p > 0.7$), again consistent with the analyses reported above.

There was also no effect of gender on the overall amplitude nor an interaction with the SNR effect for any of the eye-tracking metrics (for all $p > 0.35$).

4. Discussion

The current study investigated the extent to which eye movements can be used to measure listening challenges – here, induced by changing levels of speech masking – during story listening in younger and older adults. Participants listened to stories with varying degrees of background masking babble under different viewing conditions (blank screen, moving-dots display). The data show that eye movements decrease when speech masking increases. The pupil size seemed not very sensitive to speech masking under continuous story listening. The reduction in eye movements under speech masking did not significantly differ between viewing conditions nor age groups, suggesting that eye movements could be used as an effective way to assess listening challenges.

4.1. Effects of speech masking on pupil size decline fast during story listening

Pupil size has repeatedly been shown to increase when listening effort increases in trial-by-trial, sentence-listening paradigms (Kadem et al., 2020; Kuchinsky et al., 2013, 2014; Neagu et al., 2023; Wendt et al., 2016; Winn and Teece, 2021; Winn et al., 2015; Winn, 2016, 2017; Zekveld and Kramer, 2014; Zekveld et al., 2010, 2019; Zhang et al., 2022). Our supplementary analysis shows a transient effect of speech masking that is consistent with the work using isolated sentences (Figure S1). Other work using ~30-s speech snippets under different listening challenges found that pupil size can be sensitive to listening difficulties for longer speech segments, although these works treated pupil data similar to trial-by-trial paradigms (Fiedler et al., 2021; Seifi Ala et al., 2020; for non-speech stimuli see Zhao et al., 2019). Very few studies have used pupillometry to assess listening effort for continuous speech. In the current study, the pupil size was not sensitive to speech masking – our manipulation to induce listening effort – during story listening when the whole dataset was used in the analysis. An explorative block-wise analysis showed that pupil size increased with increasing speech masking, but only in the first experimental block. This is consistent with previous work using a story-listening paradigm that was comparable to the current study, observing that the pupil size is sensitive to speech masking when time-on-task trends are accounted for (Widmann et al., 2025). The speech masking effect in this previous study was also driven mainly by earlier parts of the story, although the effect also came out in the overall analysis (Widmann et al., 2025), whereas this was not the case here.

Potential differences between studies are that an older eye tracker was used for the current than the previous story-listening work (Cui and Herrmann, 2023; Widmann et al., 2025), potentially reducing sensitivity. Perhaps more critical, the overall pupil size appeared smaller in the current study (pupil size of 700–900; Fig. 2) than in the previous work (pupil size of 1250–1750; Cui and Herrmann, 2023; Widmann et al., 2025). Although there were no obvious differences in the ambient light conditions of the environments in which the data for these studies were recorded, the smaller pupil size might indicate that more light was reaching participants' eyes in the current than the previous work. Recommendations for recording pupillometry for assessments of listening effort favor brighter over darker ambient light conditions (Winn et al., 2018), and a relatively small overall pupil size in the current study would suggest that there is the capacity for the pupil size to increase under listening challenges. However, effects of arousal on the pupil size have been reported to depend on light level and may even be abolished at high retinal illuminance (i.e., small pupil size; Pan et al., 2024). It may thus be that retinal illuminance impacted the effect of listening effort on pupil size. A few works have suggested that individual adjustments of the ambient light level may be beneficial for assessing listening effort through pupillometry (Koelewijn et al., 2014; Ohlenforst et al., 2017; Zekveld et al., 2010, 2019). Nevertheless, another previous study from our lab, using exactly the same setup and environmental conditions as the current study, observed pupil increases during sentence listening (Herrmann and Ryan, 2024), thus indicating that sensitivity to speech masking per se is not reduced in the current setup.

Regardless of the reasons of why the pupil size may not have been as sensitive to SNR in the current than previous work, the collective data may suggest that using pupil size to assess listening effort during story listening may depend on parameters of the eye tracker, recording environment, and time-on-task, and may not be as easily observed as during trial-by-trial, sentence-listening paradigms. Optimizing the setup for pupil recordings in future work and accounting for time-on-task (Widmann et al., 2025) may thus be critical for capturing effects of SNR on the pupil size during story listening.

4.2. Eye movements are sensitive to speech masking during story listening

The current study shows that the number and distance of eye movements decrease (indexed by gaze dispersion, fixation duration, and saccade rate) when the level of background noise relative to speech increases (Figs. 3–5), consistent with a few other recent works (Contadini-Wright et al., 2023; Cui and Herrmann, 2023; He et al., 2024; Herrmann and Ryan, 2024). Eye movements may thus indicate the degree of listening effort.

Critically, the current study shows that eye movements decrease with increasing speech masking during story listening for both the free-viewing (blank screen) and moving-dots conditions. Previous studies presented a blank screen, a single dot, or a fixation cross during sentence listening or several dots during sentence or story listening (Contadini-Wright et al., 2023; Cui and Herrmann, 2023; Herrmann and Ryan, 2024). These studies jointly with the current data indicate that the reduction in eye movements during cognitively challenging listening generalizes across visual-stimulation contexts. Eye movements may thus be an effective tool, especially in situations where visual information or light conditions cannot be controlled well and where, in turn, pupillometry may be less feasible.

Older adults moved their eyes more overall (Figs. 3, 5), which is a well-known phenomenon (Liu et al., 2018; Mazloum-Farzaghi et al., 2022; Ryan et al., 2007), although the reasons for this are less clear. Critically, age group did not modulate the SNR effect, indicating that eye movement reductions due to listening challenges were mostly similar in younger and older adults. Moreover, the pure-tone average threshold, indexing the degree of a person's peripheral hearing loss (at least outer hair cell loss; Moore, 2007; Oxenham and Bacon, 2003), also did not modulate the effect of SNR on eye movements. The similar modulation of eye movements by SNR across age groups and PTAs may be somewhat surprising, given that older adults consistently show lower speech intelligibility in sentence-listening paradigms for given SNRs (Ferguson et al., 2010; Helfer and Freyman, 2008; Pandey and Herrmann, 2025; Presacco et al., 2019; Sobon et al., 2019). However, younger and older people are similarly absorbed by naturalistic stories (Mathiesen et al., 2024) and story absorption appears to be little impacted by moderate background noise (Herrmann and Johnsrude, 2020b). Older adults have also been shown to benefit well from speech context (Payne and Silcox, 2019) and tend to report as many details and comparable gist comprehension in more naturalistic, continuous listening paradigms (Gordon

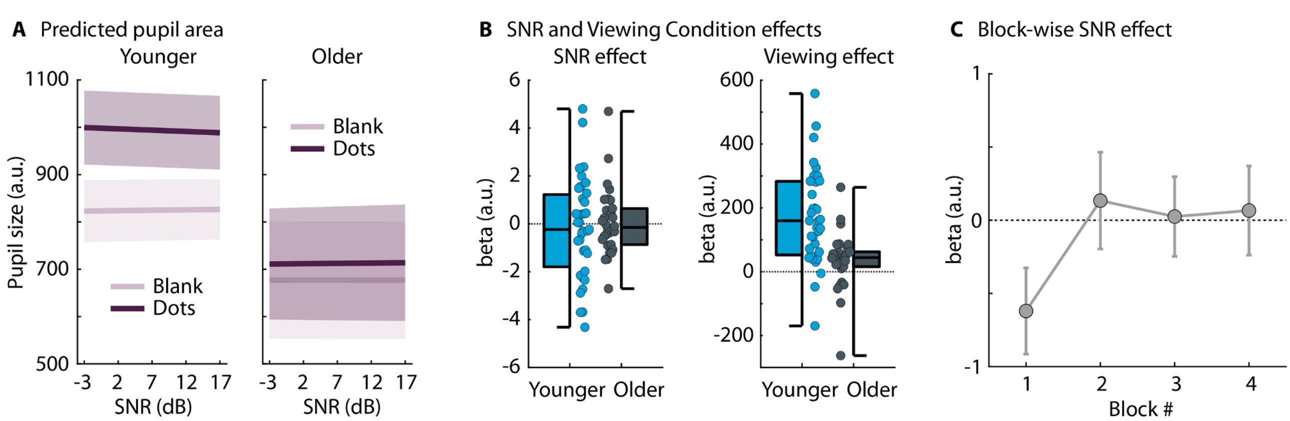

Fig. 2. Results for the pupil size. A: Predicted pupil size from fitting a linear model for each participant. The data shown reflect the residuals after removing time-on-task linear and quadratic trends. **B:** The effects of SNR and viewing condition (blank screen vs moving-dots display). The data reflect the slopes (beta values) from the linear model fits (dots are the slopes from different participants). For the SNR effect, a beta value greater than 0 indicates that the pupil size increased with increasing SNR. For the viewing-condition effect, a beta value greater than 0 indicates that the pupil size was greater for the moving-dots display than the blank screen. **C:** Mean beta values (slopes) for the SNR effect from an exploratory analysis, separately for each block of the experiment. The SNR effect was significant only for the first block.

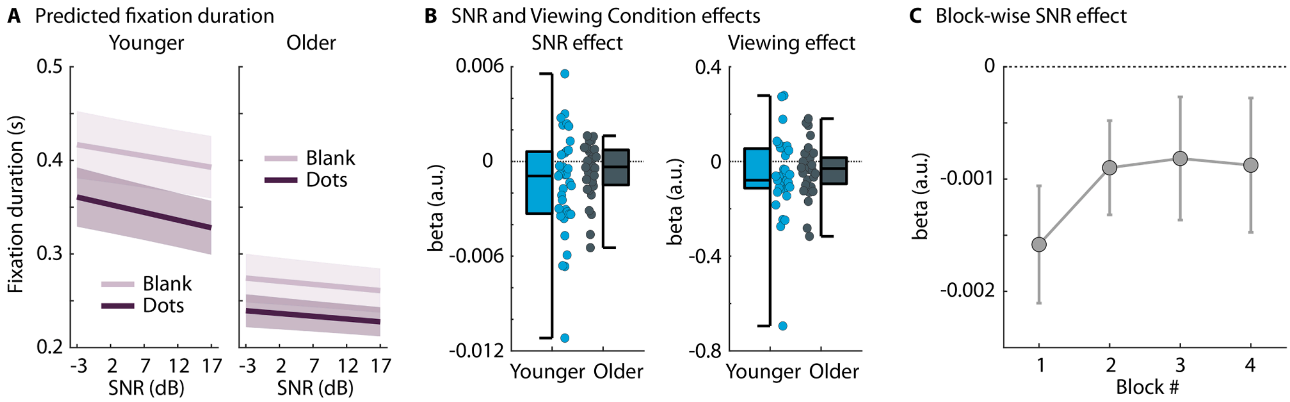

Fig. 3. Results for the fixation duration. A: Predicted fixation durations from fitting a linear model for each participant. The data shown reflect the residuals after removing time-on-task linear and quadratic trends. **B:** The effects of SNR and viewing condition (blank screen vs moving-dots display). The data reflect the slopes (beta values) from the linear model fits (dots are the slopes from different participants). For the SNR effect, a beta value smaller than 0 indicates that fixation durations decreased (i.e., more eye movements) with increasing SNR. For the viewing-condition effect, a beta value smaller than 0 indicates that fixations durations were shorter for the moving-dots display than the blank screen. **C:** Mean beta values (slopes) for the SNR effect from an exploratory analysis, separately for each block of the experiment. The SNR effect was significant for the first two blocks.

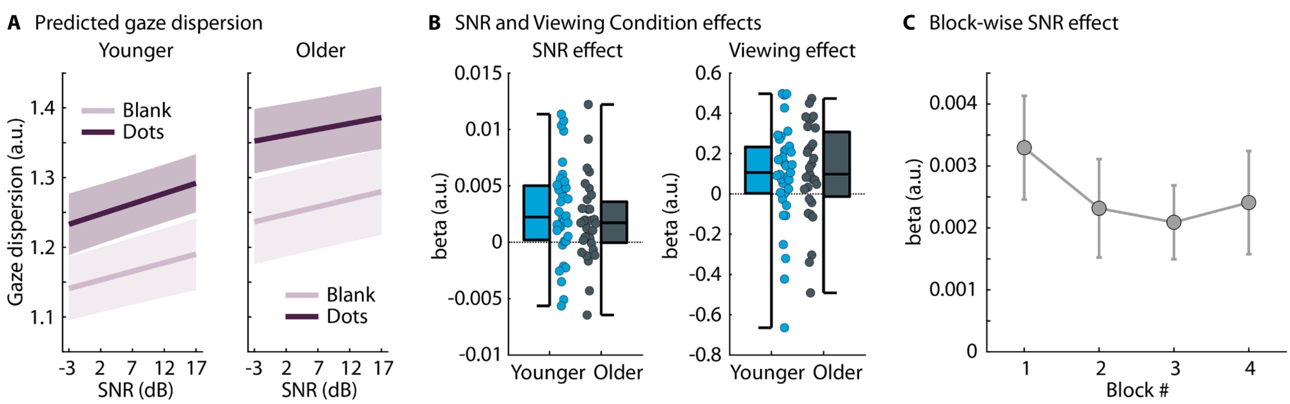

Fig. 4. Results for gaze dispersion. A: Predicted gaze dispersion from fitting a linear model for each participant. The data shown reflect the residuals after removing time-on-task linear and quadratic trends. **B:** The effects of SNR and viewing condition (blank screen vs moving-dots display). The data reflect the slopes (beta values) from the linear model fits (dots are the slopes from different participants). For the SNR effect, a beta value greater than 0 indicates that gaze dispersion increased (i.e., more eye movements) with increasing SNR. For the viewing-condition effect, a beta value greater than 0 indicates that gaze dispersion was greater for the moving-dots display than the blank screen. **C:** Mean beta values (slopes) for the SNR effect from an exploratory analysis, separately for each block of the experiment. The SNR effect was significant for all blocks.

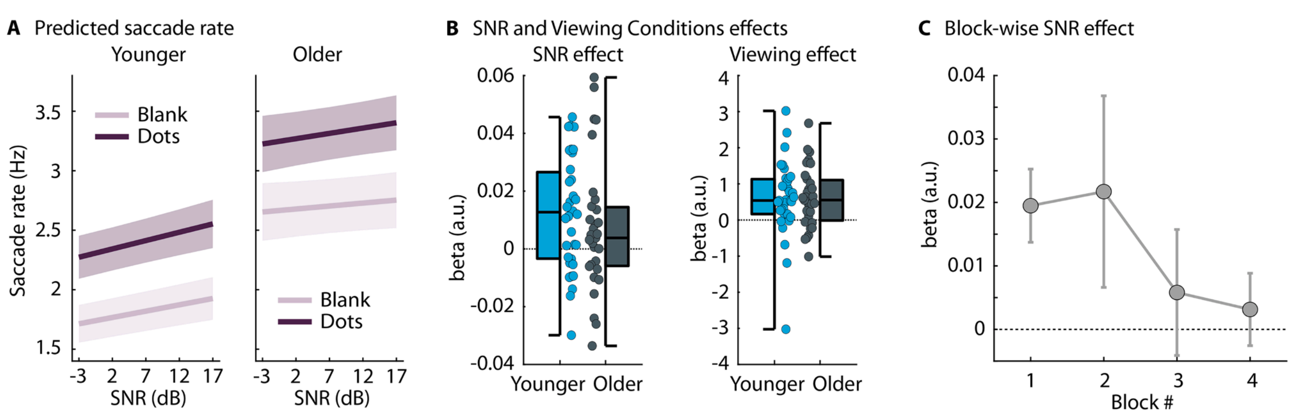

Fig. 5. Results for saccade rate. A: Predicted saccade rate from fitting a linear model for each participant. The data shown reflect the residuals after removing time-on-task linear and quadratic trends. **B:** The effects of SNR and viewing condition (blank screen vs moving-dots display). The data reflect the slopes (beta values) from the linear model fits (dots are the slopes from different participants). For the SNR effect, a beta value greater than 0 indicates that saccade rate increased (i.e., more eye movements) with increasing SNR. For the viewing-condition effect, a beta value greater than 0 indicates that saccade rate was greater for the moving-dots display than the blank screen. **C:** Mean beta values (slopes) for the SNR effect from an exploratory analysis, separately for each block of the experiment. The SNR effect was significant only for the first block; note though that block-wise estimation of the SNR effect for saccade rate was more poorly (data points are sparser for saccades).

et al., 2009). The latter is consistent with the current behavioral results showing that both younger and older adults have similarly high story-comprehension accuracy (~0.87). The current data thus provide little evidence that older adults experienced more listening effort than younger adults, but that eye movements are sensitive within participants to the listening challenges associated with speech masked by background babble.

4.3. Potential mechanisms of reduced eye movements

In the current study, we employed different analyses to capture changes in eye movements. Fixation duration and gaze dispersion have recently been used as broad measures of eye movements – that can include saccades and smooth pursuit among others – to obtain an all-encompassing measure that is sensitive to challenges during listening (Cui and Herrmann, 2023; Herrmann and Ryan, 2024). Here we also used a saccade/microsaccade rate as a more specific measure (Engbert and Kliegl, 2003; Engbert, 2006; Widmann et al., 2014), which has shown sensitivity to cognitive demands in previous studies (Contadini-Wright et al., 2023; Dalmaso et al., 2017; Kadosh et al., 2024), although not all (Kadem et al., 2020; see also Cui and Herrmann, 2023). The pattern of results of the three eye-movement metrics were very similar and correlated, suggesting that any of the metrics could be used. Nevertheless, SNR effects of gaze dispersion were significant for all experimental blocks, potentially pointing to better sensitivity (although rather numerically in the current study) especially when effects of speech masking are the main purpose of a study.

The effects of speech masking differed somewhat between the pupil size and eye-movement metrics, although it is unclear whether this reflects differences in the measures' sensitivity or different underlying mechanisms. Cortical and subcortical brain structures – such as the visual cortex, prefrontal cortex, posterior parietal cortex, frontal and supplementary eye fields, anterior cingulate cortex, cerebellum, thalamus, basal ganglia, and superior colliculus – underlie the generation and regulation of eye movements (Pierce et al., 2019; Pierrot-Deseilligny et al., 2004; Sparks, 2002). Changes in the pupil size are driven by some of the same regions (Burlingham et al., 2022, 2024; Joshi and Gold, 2020; Wang and Munoz, 2021; Wang et al., 2012), but also by regions that are less involved in eye-movement regulation, such as the locus coeruleus (Joshi and Gold, 2020; Mathôt, 2018; Strauch et al., 2022).

Changes in the pupil size are associated with changes in arousal, which in turn is driven by locus coeruleus function (Bradley et al., 2008; Burlingham et al., 2022; Mathôt, 2018; Ross and Van Bockstaele, 2021; Wang et al., 2018). The pupil size is thought to index listening effort via the arousal system, such that the higher cognitive load associated with effort increases arousal, which, in turn, increases the pupil size (Fink et al., 2024; Winn et al., 2018; Zekveld et al., 2018). Changes in eye movements are not tied into the arousal system and may thus involve different processes. Small eye movements (microsaccades) occur during fixation that would largely be considered involuntary (Alexander and Martinez-Conde, 2019; Martinez-Conde et al., 2009, 2013; although microsaccades can also be voluntarily initiated under rare conditions: Willeke et al., 2019). Eye-movement reductions due to speech masking have been observed while participants fixate on a point (Contadini-Wright et al., 2023; Cui and Herrmann, 2023), suggesting a role of involuntary eye movements. This is also consistent with work showing reductions in eye movements during fixation under high compared to low memory load (Dalmaso et al., 2017; Kadosh et al., 2024). However, a listener can also voluntarily change their eye movements (Pierce et al., 2019), for example, by fixating on a specific location to avoid visual distractions rather than engaging in visual search under challenging listening conditions.

That changes in pupil size and eye movements may index listening challenges differently is also suggested by the absence of a between-participant correlation (although saccade rate negatively correlated with pupil size when limited to the first block) and by recent work on disengagement from effortful listening (Herrmann and Ryan, 2024). When listeners disengage from listening (because comprehension is impossible) and listening effort is low as a result, the pupil size decreases (indexing lower arousal), whereas eye movements are also reduced, which would indicate greater listening effort (Herrmann and Ryan, 2024). The reasons for this are not fully understood. It is possible that when individuals disengage and orient their attention mentally inwards (e.g., think about their day) they reduce their eye movements (Herrmann and Ryan, 2024), but this requires further investigation. These previous data and to some extent the current data suggest, nevertheless, that eye movements might index speech-comprehension challenges differently than the pupil size, possibly pointing to an advantage of capitalizing on both measures when possible (cf. Contadini-Wright et al., 2023).

5. Conclusions

The current study investigated whether eye movements are sensitive to listening challenges induced through speech masking during continuous story listening, whether changes in eye movements with increased speech masking depend on visual-stimulation conditions, and whether eye-movement changes differ between younger and older adults. The results show that eye movements decrease (as indicated by fixation duration, gaze dispersion, and saccade rate) as speech masking and associated listening effort increase, and that this eye-movement reduction appears to be independent of visual-stimulation conditions and does not differ between younger and older adults. The data suggest that eye movements could potentially be used as a measure of listening effort during continuous story listening.

Data availability

Data will be available to other researchers upon reasonable request to the corresponding author.

CRediT authorship contribution statement

Björn Herrmann: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Florian Scharf:** Writing – review & editing, Methodology, Formal analysis. **Andreas Widmann:** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

The author has no conflicts or competing interests.

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