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Research Article

The Influence of Hearing Loss on Cognitive Control in an Auditory Conflict Task: Behavioral and Pupillometry Findings

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Purpose: The pupil dilation response is sensitive not only to auditory task demand but also to cognitive conflict. Conflict is induced by incompatible trials in auditory Stroop tasks in which participants have to identify the presentation location (left or right ear) of the words “left” or “right.” Previous studies demonstrated that the compatibility effect is reduced if the trial is preceded by another incompatible trial (conflict adaptation). Here, we investigated the influence of hearing status on cognitive conflict and conflict adaptation in an auditory Stroop task.

Method: Two age-matched groups consisting of 32 normal-hearing participants ($M_{\text{age}} = 52$ years, age range: 25–67 years) and 28 participants with hearing impairment ($M_{\text{age}} = 52$ years, age range: 23–64 years) performed an auditory Stroop task. We assessed the effects of hearing status and stimulus compatibility on reaction times (RTs) and pupil dilation responses. We furthermore analyzed the Pearson correlation coefficients between age, degree of hearing loss, and the

compatibility effects on the RT and pupil response data across all participants.

Results: As expected, the RTs were longer and pupil dilation was larger for incompatible relative to compatible trials. Furthermore, these effects were reduced for trials following incompatible (as compared to compatible) trials (conflict adaptation). No general effect of hearing status was observed, but the correlations suggested that higher age and a larger degree of hearing loss were associated with more interference of current incompatibility on RTs.

Conclusions: Conflict processing and adaptation effects were observed on the RTs and pupil dilation responses in an auditory Stroop task. No general effects of hearing status were observed, but the correlations suggested that higher age and a greater degree of hearing loss were related to reduced conflict processing ability. The current study underlines the relevance of taking into account cognitive control and conflict adaptation processes.

The measurement of the pupil dilation response is a means to gain insight into mental effort mobilization (Beatty, 1982; Kahneman & Beatty, 1966). Effort mobilization is the mobilization of energy resources to complete a (cognitive) task (Gendolla et al., 2011). The method has been applied to study listening effort (Eckstein

et al., 2017; Schmidtke, 2018; Sirois & Brisson, 2014; for a review, see Zekveld et al., 2018). The pupil diameter increases when intelligibility decreases (or when auditory task demand increases), as long as the listeners continue to try to perceive the speech (Koelewijn et al., 2012; Ohlenforst et al., 2017; Zekveld & Kramer, 2014; Zekveld et al., 2018). The pupil response, as a function of a wide range of task demand levels, follows an inverted U-shaped function (Ohlenforst et al., 2017; Zekveld & Kramer, 2014). This is in line with theories postulating that task difficulty and motivation influence the effort invested in a task (Brehm & Self, 1989; Richter et al., 2008, 2016). Following these theories, effort mobilization decreases when the task becomes too difficult. Several studies have shown that the pupil dilation response during listening differs between listeners with normal hearing (NH) and those with hearing impairment (HI; Kramer et al., 1997; Ohlenforst et al., 2017; Wang et al., 2018; Zekveld

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et al., 2011; for a review, see Zekveld et al., 2018). Often, an interaction with speech intelligibility is observed, such that the pupil response of listeners with HI is relatively small in very difficult listening conditions (Ohlenforst et al., 2017; Wang et al., 2018; Zekveld et al., 2011). This may indicate a shift in the inverted U-shaped function of pupil dilation as function of task demand for listeners with HI as compared to NH listeners, or fatigue and/or withdrawal in individuals with HI in difficult conditions.

Currently, the specific nature of the impact of hearing loss on the processing of auditory information is unclear (Peelle, 2018; Pichora-Fuller et al., 2016; Zekveld et al., 2018). However, several studies point to a potential role of cognitive control processes. “Cognitive control” is a process that facilitates goal-directed behavior and is involved in the inhibition of automatic response tendencies (Botvinick et al., 2001). It is relevant for tasks in multiple cognitive domains, including updating, inhibition, and switching (Miyake et al., 2000).

A classic task specifically tapping into inhibition is the Stroop task (Stroop, 1935). Participants are asked to name the color of printed words. In compatible trials, the color of the words matches the printed name of the color. In incompatible trials, the names of the colors are printed in a different color. As a result, the correct response does not follow the natural response tendency during incompatible trials. This causes “conflict,” which slows down the response as compared to compatible trials. Once a conflict arises, cognitive control processes have been assumed to become activated to facilitate the selection of the correct response in the next trial, an effect commonly referred to as “conflict adaptation.” This effect can be assessed by analyzing “trial-to-trial effects” of conflicting conditions. Analyses of such sequential effects have shown that the behavioral interference arising from a conflict trial is reduced if the trial is preceded by another conflict trial (Gratton et al., 1992; Kerns et al., 2004; for reviews, see Duthoo et al., 2014; Egner, 2007). This possibly reflects an online adaptation process triggered by previous conflict, which continues to affect the responses on the following trial (Scherbaum et al., 2011).

The influence of cognitive conflict on effort mobilization has been assessed by measuring the pupil dilation response. Numerous studies that applied various conflict tasks, including the Stroop, flanker, and Simon tasks, have observed that incompatible trials are associated with longer reaction times (RTs) and larger pupil dilation responses as compared to compatible trials (for a review, see van der Wel & van Steenbergen, 2018). Furthermore, the analysis of the trial-to-trial (sequential) compatibility effects has revealed that the typical conflict adaptation effect in RT is mirrored by pupil dilation effects (van Steenbergen & Band, 2013; for a replication, see D’Ascenzo et al., 2016). Moreover, van Steenbergen et al. (2015) showed that the magnitude of the behavioral conflict adaptation effect depends on task difficulty. They observed that increasing perceived task difficulty eliminated behavioral conflict adaptation. Specifically, the interaction reflecting a smaller compatibility

effect after conflict trials disappeared. Van Steenbergen et al. suggested that this possibly indicates a failure to recruit sufficient effort after conflict in difficult conditions, in line with the inverted U-shaped function of effort mobilization across task difficulty levels.

The potential role of cognitive control processes during speech perception in difficult conditions has been suggested by a few neuroimaging studies. For example, Vaden et al. (2015) performed a functional magnetic resonance imaging study and showed that increased activity in the anterior cingulate cortex (ACC) was associated with better perception of words presented in background babble by both participants with NH and HI. The ACC is associated with the monitoring and adjustment of behavior to optimize performance, processes that are relevant to cognitive control (Dosenbach et al., 2006; Roberts & Hall, 2008). Higher activation in the ACC was associated with increased performance on the next trial, suggesting that cognitive control processes support word recognition in difficult listening conditions. This effect was larger for participants with better overall performance, and it declined with increasing age. In general, previous studies have shown that increasing age is related to worse inhibition ability and cognitive control (for a review, see Braver & Barch, 2002). Consistent with the relevance of cognitive conflict during listening, Zekveld et al. (2014) observed an association between activation in the ACC and prefrontal areas and the pupil dilation response of young NH participants in demanding listening conditions (Zekveld et al., 2014).

The Current Study

Based on the studies described above, we aimed to investigate the influence of hearing status on cognitive control and conflict adaptation processes as evoked by an auditory Stroop task (Buzzell et al., 2013; Oh et al., 2012). In this task, the word “left” or “right” was monaurally presented through headphones to either the left or right ear. The participants were instructed to indicate the sound location while ignoring the meaning of the presented stimuli. In incompatible trials (e.g., the word “left” presented to the right ear), the tendency to indicate the meaning of the word needs to be inhibited, which results in cognitive conflict (Buzzell et al., 2013; Oh et al., 2012). In line with a large body of research, we hypothesized that the response time and pupil dilation response would be larger for incompatible compared to compatible trials. Furthermore, we expected that these compatibility effects would be reduced in trials that were preceded by other incompatible trials (conflict adaptation processes; van Steenbergen & Band, 2013). We further hypothesized that hearing status might be associated with altered cognitive control processing in an auditory task. Note that, theoretically, listeners with HI may experience an advantage of their hearing loss in this task because any difficulty in perceiving the meaning of the distracting words may reduce the interference between distractor (word meaning) and target (stimulus location) in incompatible trials.

Therefore, we adapted the presentation level of the stimuli to degree of hearing loss separately for both ears.

Method

Participants

Sixty-three participants were included. However, for three of them, no valid data were collected due to logistic issues. Of the 60 remaining participants, 32 were with NH (22 women, 10 men; $M_{\text{age}} = 52$ years, age range: 25–67 years, $SD = 10.9$ years). Furthermore, 28 participants with HI were included (13 women, 15 men; $M_{\text{age}} = 52$ years, age range: 23–64 years, $SD = 11.4$ years). The participants in the two groups were matched on age.

NH participants were recruited through flyers posted around the VU University campus and VU University Medical Center. The mean pure-tone hearing thresholds of the NH participants were at most 20 dB HL at octave frequencies between 500 and 4000 Hz in the best ear. The thresholds of the other ear were at most 25 dB HL for the octave frequencies between 500 and 2000 Hz and at most 40 dB HL at 4000 Hz. Figure 1 shows the air-conduction hearing thresholds at the octave frequencies between 250 and 8000 Hz. All had normal tympanograms.

The adults with HI were recruited among the patients of the audiology clinic of the VU University Medical Center and by posting digital flyers on relevant web pages. Pure-tone, unaided air- and bone-conduction thresholds of both ears and speech recognition data were available for all participants. The pure-tone air-conduction hearing thresholds averaged across 1000, 2000, and 4000 Hz (pure-tone average [PTA]) had to be between 35 and 70 dB HL for each ear for inclusion in the current study. The hearing loss had to be sensorineural (max of a 10-dB difference between the air- and bone-conduction thresholds at 500, 1000, and 2000 Hz

in each ear and normal tympanograms). Furthermore, the recognition of Dutch consonant–vowel–consonant words (Bosman & Smoorenburg, 1995) of both ears had to be at least 80% for inclusion in the current study to ensure sufficient hearing acuity to perform the auditory Stroop tests (see below).

For all participants, additional inclusion criteria were as follows: using spoken language to communicate in daily life, being native speakers of Dutch, and not using sign language. Exclusion criteria were having neurological, psychological, endocrine, and cardiovascular diseases or diabetes. Two listeners with NH and seven listeners with HI had asymmetrical hearing loss (i.e., their left and right pure-tone hearing thresholds differed more than 20 dB at one octave frequency, more than 15 dB at two octave frequencies, or more than 10 dB at three octave frequencies between 250 and 4000 Hz).

The experiment was approved by the local ethics committee, and all participants gave written informed consent. Participants received a small monetary compensation for their participation and travel expenses related to participation.

The sample size was based on an a priori power analysis. We were mainly interested in the interaction between hearing status and the effect of stimulus compatibility as tested using a repeated-measures analysis of variance (ANOVA; for details, see the Statistical Analysis section). As no previous data were available regarding the effect of hearing status on auditory Stroop effects in age-matched groups, we assumed a medium effect-sized ($f = .15$) interaction. To detect this effect with $\alpha = .05$ and power ($1 - \beta$) = .80, 62 participants were required in total (G*Power Version 3.1.9.2; Erdfelder et al., 1996).

Procedure

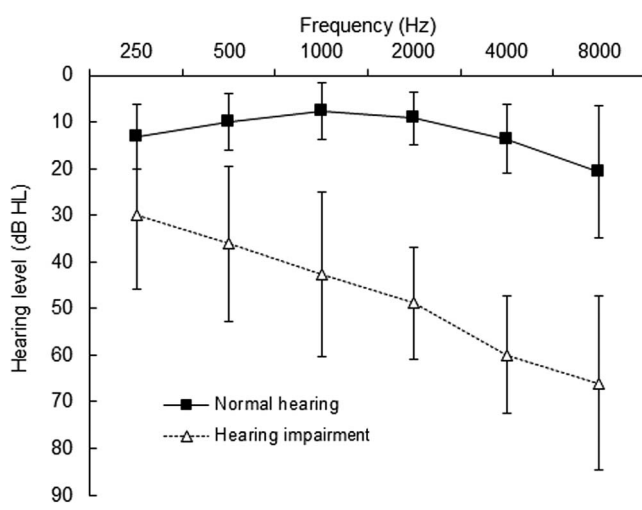
Participants performed the auditory Stroop task as a part of an experimental test session consisting of multiple tests (reported elsewhere; Zekveld et al., 2019). They were seated behind a PC screen at an approximately 60-cm distance. The test was performed in a sound-treated room.

Auditory Stroop Task

The auditory stimuli consisted of either the Dutch word *rechts* (“right,” duration of 642 ms) or *links* (“left,” duration of 616 ms). The words were pronounced by a native female speaker. Stimuli were presented via headphones at 65 dB SPL. To optimize audibility for the listeners with HI, we applied frequency-specific amplification separately for both ears based on the individual’s audiogram using the NAL-R algorithm (Byrne & Dillon, 1986). We applied one third of octave steps within the frequency range of 300–6300 Hz. An audibility check was performed by asking participants to repeat sentences presented in quiet. There were no differences between the listeners with NH and those with HI in their ability to do so.

The stimuli were presented at either the left or right ear. Participants were instructed to identify the side at

Figure 1. Mean (across ears) pure-tone air-conduction thresholds for each octave frequency. Error bars indicate 1 *SD*.



which they heard the sound as quickly and accurately as possible. A response box was used with two buttons: one on the left side of the box and one on the right side of the box. This answering device rested on the participants' lap and fitted comfortably in the participants' hands. Participants used both thumbs to answer and did not receive feedback about their performance.

In total, 80 stimuli were presented to the participants. Half of the stimuli were presented to the left ear, and half were presented to the right ear. Forty trials were "compatible," meaning that the ear and the stimulus matched (e.g., the word "left" presented to the left ear). In the remaining 40 "incompatible" trials, the ear and stimulus did not match (e.g., the word "left" presented to the right ear). For both types of trials, half (20) were presented to the left ear and half were presented to the right ear. The order of conditions was randomized with the restriction that the trial sequence did not include exact stimulus repetitions, as these can result in stimulus repetition effects (Mayr et al., 2003). Participants were allowed to respond directly after stimulus onset, and after their response, the next stimulus was presented after a 3000-ms interval. Figure 2 illustrates the timing of trials. We recorded the manual RT and accuracy of the response.

Pupillometry

During the Stroop task, the pupil size was recorded using a SMI RED remote eyetracker at 60 Hz. First, a standard gaze calibration procedure was performed. Then, the ambient illumination level was set to the middle of the dynamic range of the pupil size of each participant (Beatty & Lucero-Wagoner, 2000; Hyönä et al., 1995; Janisse, 1977; Zekveld et al., 2010) and remained at that level during the experiment. During the test, a gray fixation dot was visible at the center of the black screen. Participants were instructed to keep their gaze on the dot to allow optimal registration of the pupil size and to reduce eye movement-related artifacts in the measurement of the pupil size.

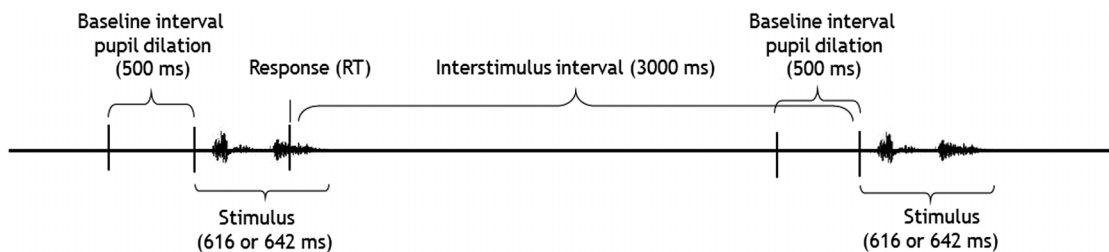
The pupil data of the right eye were used in the analysis. For one patient, it was required to use the data of the left eye due to a medical condition only affecting the right eye. For all participants, we excluded the data of the first trial, of the incorrect trials, of the trials following an incorrect response, of trials with RTs > 3000 ms, and of trials with poor quality of the pupil data in the pretrial baseline

interval (see below). Pupil diameters below 3 *SDs* of the mean diameter during each trial were coded as a blink. If the data contained more than 50% blinks in the interval of interest, the data for this trial were also excluded from the analysis (van Steenbergen & Band, 2013). Eye blinks were replaced by linear interpolation starting four samples before and ending eight samples after a blink. The data were then passed through a 5-point moving average smoothing filter. The pretrial baseline pupil size was the average pupil size in the 500-ms window prior to stimulus presentation. We averaged the pupil data over trials for each condition and individual. Subsequently, we calculated the mean pupil dilation and maximum (peak) pupil dilation relative to the baseline pupil size in the interval between the onset of the stimulus and the end of the trial (fastest RT in that particular condition plus 2500 ms).

Statistical Analysis

In the first repeated-measures ANOVA analysis, we tested the effects of "hearing status" (NH, HI) and "compatibility" (incompatible, compatible) on RT. For the second analysis, the trials were grouped into four sequential conditions: current compatible after previous compatible trials (cC), current incompatible after previous compatible trials (cI), current incompatible after previous incompatible trials (iI), and current compatible after previous incompatible trials (iC). We performed a repeated-measures ANOVA on these data testing for the effects of the compatibility of the current trial (current compatibility: compatible vs. incompatible), the compatibility of the previous trial (previous compatibility: compatible vs. incompatible), and hearing status (NH vs. HI) on RT. Similar repeated-measures multivariate ANOVAs (MANOVAs) were performed on the pupil response data (mean and peak pupil dilation response). We decided to include both the peak and mean pupil dilation response to improve the generalizability of the results, as previous studies have been using both measures interchangeably. As the peak and mean pupil dilation response are associated with each other, a multivariate analysis approach was appropriate. Finally, we tested the effects of hearing status, current compatibility, and previous compatibility on the baseline pupil size to check that any sequential effects on the mean and peak pupil response were not caused by sustained effects of the previous trial on the baseline pupil size.

Figure 2. Timing of trials. RT = reaction time.



To assess the hypothesized effect of degree of hearing loss on conflict processing and conflict adaptation, we further calculated the correlation coefficients between degree of hearing loss (mean PTA across ears), age, the compatibility effect (incompatible trials minus compatible trials), and the conflict adaptation effect on the RT as well as mean and peak pupil dilation data across all participants (with NH and HI).

Results

Table 1 shows the descriptive statistics of the error rates, RTs, mean pupil dilation, and peak pupil dilation relative to the baseline pupil size.

Behavioral Results

We did not perform statistical analyses on the error rate data, as the participants only made a few errors and these data were not normally distributed. The error rate was relatively low (on average, less than 1%) as compared to those in previous studies (Rondeel et al., 2015; van Steenbergen & Band, 2013).

The repeated-measures ANOVA testing the effects of hearing status (NH vs. HI) and compatibility (compatible vs. incompatible) on the RTs indicated a main effect of compatibility, $F(1, 58) = 89.2, p < .001$, partial $\eta^2 = .61$, but no other effects (all partial η^2 values $< .05$). The compatibility effect indicated that RTs for incompatible trials were slower than those for compatible trials, indicating the task successfully induced conflict.

Pupil Dilation Response

Figure 3 shows the pupil dilation response to compatible and incompatible trials, separately for the listeners with NH and HI. A repeated-measures MANOVA with the factors compatibility and hearing status was performed on the mean and peak pupil dilation response. It indicated a main multivariate effect of compatibility, with a larger mean pupil dilation for incompatible relative to compatible trials, $F(2, 57) = 7.2, p < .01$, partial $\eta^2 = .20$. There was no multivariate effect of hearing status or an interaction between compatibility and hearing status (all partial η^2 values $< .006$). The pattern of multivariate results was similar to the univariate results that included either the mean or peak pupil dilation response data: main effect of compatibility on the mean pupil dilation response, $F(1, 58) = 14.6, p < .001$, partial $\eta^2 = .20$, and on the peak pupil dilation response, $F(1, 58) = 11.2, p < .001$, partial $\eta^2 = .16$.

Sequential Effects

Table 2 shows the descriptive statistics of the RTs as well as mean and peak pupil dilation data for the analysis of the sequential effects.

Sequential Effects of RTs

A repeated-measures ANOVA with factors hearing status (NH vs. HI), current compatibility (compatible vs. incompatible), and previous compatibility (compatible vs. incompatible) on the RT data indicated a main effect of current compatibility, $F(1, 58) = 77.5, p < .001$, partial $\eta^2 = .57$, and an interaction effect between current compatibility and previous compatibility, $F(1, 58) = 24.8, p < .001$, partial $\eta^2 = .30$. The main effects of previous compatibility and hearing status and the other interaction effects were not statistically significant (all partial $\eta^2 < .04$). Figure 4 shows the RTs organized relative to current and previous compatibility. These results indicated the standard conflict adaptation effect: incompatible trials were associated with longer RTs than compatible trials, but this effect was reduced after incompatible trials.

Paired-samples *t* tests were performed to test for pairwise differences in RT across previous and current compatibility conditions. The results are presented in Table 3.

Sequential Effects of Pupil Dilation Response

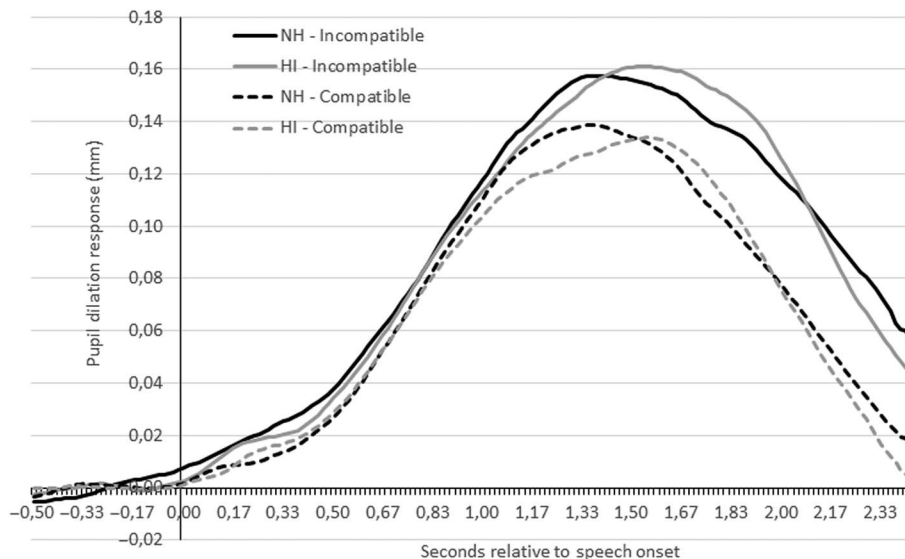
A MANOVA with the same factors was performed on the mean and peak pupil dilation response data (see Figure 5). The MANOVA indicated a main effect of current compatibility, $F(2, 57) = 3.5, p = .039$, partial $\eta^2 = .11$, as well as a main effect of previous compatibility, $F(2, 57) = 5.2, p < .01$, partial $\eta^2 = .15$. Furthermore, the interaction between previous and current compatibility was significant, $F(2, 57) = 5.9, p < .01$, partial $\eta^2 = .17$, reflecting a smaller effect of current compatibility after incompatible trials relative to compatible trials.

The subsequent univariate analyses of the mean and peak pupil dilation response data indicated that both main multivariate effects were based on the mean and peak pupil dilation. Namely, we observed a main effect of current compatibility on the mean pupil dilation response, $F(1, 58) = 7.0, p = .01$, partial $\eta^2 = .11$, and on the peak dilation response, $F(1, 58) = 4.9, p = .03$, partial $\eta^2 = .08$. Also, the univariate effect of previous compatibility was significant for both the mean pupil dilation response, $F(1, 58) = 6.9, p = .01$, partial

Table 1. Means (standard deviations) of the error rate, reaction times (RTs), and mean and peak pupil dilation response relative to the baseline pupil size for compatible (Comp.) and incompatible (Incomp.) trials, separately for the best and worst ear. NH = normal hearing; HI = hearing impairment.

Group	Error rate (no. incorrect)		RT (ms)		Mean pupil dilation (mm)		Peak pupil dilation (mm)	
	Comp.	Incomp.	Comp.	Incomp.	Comp.	Incomp.	Comp.	Incomp.
NH	0.02 (0.09)	0.5 (0.8)	708 (115)	786 (142)	0.06 (0.05)	0.09 (0.06)	0.16 (0.09)	0.18 (0.09)
HI	0.04 (0.1)	0.9 (30.0)	737 (165)	847 (221)	0.06 (0.06)	0.09 (0.06)	0.16 (0.09)	0.18 (0.09)

Figure 3. Pupil dilation response during listening. The pupil dilation response (mm) is relative to the average pupil size in the baseline interval between -0.5 and 0 s. NH = normal hearing; HI = hearing impairment.



$\eta^2 = .11$, and for the peak pupil dilation response, $F(1, 58) = 10.4, p < .01$, partial $\eta^2 = .15$. The multivariate interaction between previous and current compatibility was driven by the mean pupil dilation response data, for which the interaction approached significance, $F(1, 58) = 2.9, p = .09$, partial $\eta^2 = .05$.

These main and interaction effects of previous and current compatibility on the pupil response were not associated with a larger pupil baseline diameter after incompatible trials. Also, the effects of hearing status on the baseline pupil size were not significant (all partial $\eta^2 < .03$).

Correlation Analyses

In order to test our hypothesis that age and degree of hearing loss influence cognitive control processes, we calculated the Pearson correlation coefficients between age, degree of hearing loss (mean PTA across ears), and the compatibility effect of the current trial (incompatible trials minus compatible trials) on the RT as well as mean and peak pupil dilation data (see Table 4). These coefficients

were calculated across all participants (with NH and HI). Table 4 also shows the correlation coefficients between age, degree of hearing loss, and the conflict adaptation effect (i.e., the difference in the compatibility effect on the RT as well as mean and peak pupil dilation between trials preceded by compatible relative to incompatible trials: $[cI - cC] - [iI - iC]$). A larger conflict adaptation effect indicates that the current compatibility effect was reduced after incompatible relative to compatible trials.

The results indicated that higher age and more severe hearing loss were associated with a stronger current compatibility effect on the RT data (longer RTs for incompatible vs. compatible current trials). Thus, although the audibility of the auditory stimuli was adapted to the degree of hearing loss, participants with more severe hearing loss showed more cognitive control impairment on the task.

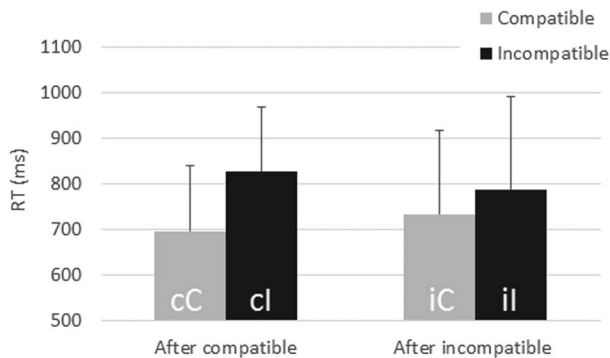
Neither age nor the degree of hearing loss was associated with the average RT across conditions, suggesting that the relationships described above were not due to general age- or hearing-related slowing.

Table 2. Mean number of trials per participant in each group (normal hearing [NH], hearing impairment [HI]), reaction times (RTs; ms), mean and peak pupil dilation response (mm) relative to the baseline pupil size for compatible after compatible trials (cC), compatible after incompatible trials (iC), incompatible after compatible trials (cI), and incompatible after incompatible trials (iI).

Variable	cC		iC		cI		iI	
	NH	HI	NH	HI	NH	HI	NH	HI
Mean number of trials	12.2	11.9	24.4	24.3	24.3	24.4	11.6	11.5
RT (ms)	684 (128)	710 (159)	718 (113)	750 (169)	799 (145)	860 (218)	761 (156)	819 (249)
Mean pupil response (mm)	0.06 (0.07)	0.08 (0.06)	0.07 (0.05)	0.05 (0.07)	0.10 (0.06)	0.09 (0.07)	0.07 (0.07)	0.07 (0.06)
Peak pupil response (mm)	0.17 (0.11)	0.19 (0.09)	0.17 (0.08)	0.15 (0.10)	0.20 (0.10)	0.20 (0.10)	0.17 (0.09)	0.18 (0.07)

Note. Standard deviations are presented inside parentheses.

Figure 4. Reaction time (RT) data as a function of previous and current compatibility. Error bars indicate 1 SD. cC = compatible after compatible trials; cl = incompatible after compatible trials; iC = compatible after incompatible trials; il = incompatible after incompatible trials.



Also, the compatibility effect observed on the RT data was positively associated with the compatibility effect on the mean and peak pupil response data. This indicates that individuals with relatively long RTs to incompatible trials (relative to compatible trials) had relatively large pupil dilation responses for these trials as well. Furthermore, those individuals also had a relatively small conflict adaptation effect as reflected in the mean and peak pupil dilation response. In other words, those who experienced less interference from incompatibility on the current trial also showed relatively small compatibility effects on the pupil data in subsequent trials. Finally, the compatibility and conflict adaptation effects in the mean pupil dilation were associated with those effects in the peak pupil dilation.

Discussion

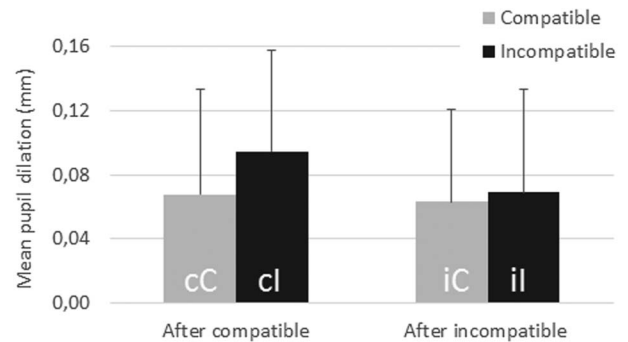
The main result of this study was that an auditory Stroop task evoked cognitive conflict processes as well as conflict adaptation processes in listeners with NH and HI. The cognitive conflict was reflected in longer RTs and larger pupil dilation responses for trials in which the identity of

Table 3. Pairwise differences (two-sided paired-samples *t* tests, Bonferroni-corrected *p* values are reported) between the RTs for compatible after compatible trials (cC), compatible after incompatible trials (iC), incompatible after compatible trials (cl), and incompatible after incompatible trials (il).

Comparison	Pairwise test statistic
cC < iC	$t(59) = -5.3^{**}$
cC < cl	$t(59) = -11.1^{***}$
il < cl	$t(59) = -2.86^*$
iC < il	$t(59) = -3.79^{**}$

* $p < .05$. ** $p < .01$. *** $p < .001$.

Figure 5. Mean pupil response data as a function of previous and current compatibility. Error bars indicate 1 SD. cC = compatible after compatible trials; cl = incompatible after compatible trials; iC = compatible after incompatible trials; il = incompatible after incompatible trials.



the auditory word did not match the presentation side of the stimulus. As a larger pupil dilation response has been associated with larger effort mobilization, this suggests that incompatibility between stimulus identity and presentation location increases the effort required to perform the task. This replicates previous studies that demonstrated such compatibility effects in conflict tasks using behavioral and physiological measures (e.g., Duthoo et al., 2014; Egner, 2007; van der Wel & van Steenbergen, 2018). We did not observe a general effect of hearing status on the compatibility effect observed in the auditory Stroop task. This suggests that cognitive control processes were not affected in listeners with HI in comparison to NH listeners. However, the correlation analysis did suggest that higher age and a larger degree of hearing loss were associated with slower RTs to incompatible (relative to compatible) trials. Note that age and hearing loss were not associated in this age-matched sample. Previous studies suggested that increasing age is indeed related to worse inhibition ability and cognitive control (Vaden et al., 2015, 2013; for a review see Braver & Barch, 2002).

A main finding of the current study was the sequential effect observed in the RT and pupil response data. RTs were slower, and the pupil response was larger for incompatible than compatible trials, but this compatibility effect was reduced after a previous incompatible (relative to compatible) trial. This interaction was in line with the expected effect of conflict adaptation processes and replicates previous findings (e.g., Donohue et al., 2012). This implies that both the performance (RTs) and the pupil response observed in auditory tasks that induce cognitive conflict may be influenced by transient processes evoked in the previous trial. This is relevant for studies that apply cognitive control tests and assess the factors influencing the performance and/or effort mobilization during such tasks (e.g., Knight & Heinrich, 2017). Moreover, as more general speech perception tasks likely also tap into cognitive control (Tai & Husain, 2019; Vaden et al., 2015, 2016), the current study supports the relevance of taking into account potential

Table 4. Pearson correlation coefficients between age, mean pure-tone average (PTA) across ears, and difference in reaction time (RT), mean and peak pupil data for incompatible minus compatible current (compatibility effect), and conflict adaptation effects (difference in compatibility effect between trial preceded by compatible vs. incompatible trials: [cI – cC] – [iI – iC]).

Variable	1	2	3	4	5	6	7
1. Age	—						
2. PTA	.00	—					
3. Compatibility effect on RT	.32*	.27*	—				
4. Compatibility effect on mean pupil response	.10	.09	.28*	—			
5. Compatibility effect on peak pupil response	.11	.10	.32*	.90**	—		
6. Conflict adaptation effect on RT	.01	.00	-.06	.04	.10	—	
7. Conflict adaptation on mean pupil dilation response	-.17	-.15	-.31*	.08	.18	-.03	—
8. Conflict adaptation effect on peak pupil dilation response	-.11	-.19	-.28*	.08	.14	-.03	.88**

* $p < .05$. ** $p < .001$.

sequential effects when analyzing performance and physiological data of listeners with NH and HI during speech perception. Such effects may be relatively large when speech perception tasks are applied that depend to a larger extent on inhibition, updating, or switching ability. These tasks may include tests with varying difficulty levels between trials, such as in the adaptive speech reception threshold tests (Plomp & Mimpen, 1979). Future studies should further examine the occurrence of conflict adaptation processes in speech perception tests.

Finally, the current study replicates previous findings demonstrating that interindividual differences in the increase in RT in response to conflict are associated with interindividual differences in the increase in pupil response related to the conflict (Laeng et al., 2011; Rondeel et al., 2015). This study further shows that individuals who show a smaller effect of current compatibility in their RTs also show stronger conflict adaptation effects on the pupil dilation response. Hence, cognitive control in a conflict task is associated with a transient ability to recruit cognitive effort after conflict performance. In this study, the performance was very high for both groups. In more difficult tests, the opposite relationship (i.e., a failure to recruit cognitive effort after conflict) has been observed (van Steenbergen et al., 2015).

Note that, apart from the association between higher age and larger degree of hearing loss with a larger effect of current compatibility on the RTs, we did not observe a main or interaction effect of hearing status on cognitive conflict and conflict adaptation effects. Thus, these processes are likely similarly effective in listeners with NH and HI. As described in the introduction, previous studies have suggested that the influence of hearing loss on the pupil dilation response is especially pronounced in difficult conditions (Ohlenforst et al., 2017; Zekveld et al., 2011). Therefore, more research is needed to assess whether the relatively small pupil dilation response of listeners with HI in such conditions is associated with altered conflict processing. Namely, as hearing loss often leads to increased listening difficulty, this may reduce the effort mobilization after conflict and thereby reduce the strength of conflict adaptation effects (van Steenbergen et al., 2015).

One of the limitations of the current study was the relatively small number of trials. This may explain the absent interaction between hearing status and stimulus compatibility on the RTs in the ANOVA, despite the significant correlation between degree of hearing loss and this effect. An increase in the number of trials would increase the reliability of the results as several trials had to be omitted from the analysis (e.g., incorrect trials and trials following an incorrect response). Furthermore, it would be interesting to apply an auditory Stroop task in which the participants would have to identify the word instead of the presentation location, as hearing loss may differentially affect this task as compared to the current localization task. Finally, the application of a visual conflict task may allow testing whether any effects of hearing status generalize to the visual modality.

In conclusion, this is the first study demonstrating the effects of current and previous stimulus compatibility in an auditory Stroop task on RT and pupillometry data in listeners with NH and HI. Incompatibility between the location and identity of the stimulus words resulted in a slower response and larger pupil dilation responses as compared to compatible stimuli. The correlation analysis suggested that this interference effect was stronger with increasing age and increasing degree of hearing loss. The RT and pupillometry data further demonstrated conflict adaptation processes. The current study may inspire future research assessing the effects of hearing acuity on conflict processing and their potential impact on behavioral and pupillometry findings in more standard speech perception tasks.

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References

- Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin*, 91(2), 276–292. <https://doi.org/10.1037/0033-2909.91.2.276>

- Beatty, J., & Lucero-Wagoner, B.** (2000). The pupillary system. In J. T. Cacioppo, L. G. Tassinary, & G. Berntson (Eds.), *Handbook of psychophysiology* (2nd ed., pp. 142–162). Cambridge University Press.
- Bosman, A. J., & Smoorenburg, G. F.** (1995). Intelligibility of Dutch CVC syllables and sentences for listeners with normal hearing and with three types of hearing impairment. *Audiology, 34*(5), 260–284. <https://doi.org/10.3109/00206099509071918>
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D.** (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624–652. <https://doi.org/10.1037/0033-295X.108.3.624>
- Braver, T. S., & Barch, D. M.** (2002). A theory of cognitive control, aging cognition, and neuromodulation. *Neuroscience & Biobehavioral Reviews, 26*(7), 809–817. [https://doi.org/10.1016/S0149-7634\(02\)00067-2](https://doi.org/10.1016/S0149-7634(02)00067-2)
- Brehm, J. W., & Self, E. A.** (1989). The intensity of motivation. *Annual Review of Psychology, 40*(1), 109–131. <https://doi.org/10.1146/annurev.ps.40.020189.000545>
- Buzell, G. A., Roberts, D. M., Baldwin, C. L., & McDonald, C. G.** (2013). An electrophysiological correlate of conflict processing in an auditory spatial Stroop task: The effect of individual differences in navigational style. *International Journal of Psychophysiology, 90*(2), 265–271. <https://doi.org/10.1016/j.ijpsycho.2013.08.008>
- Byrne, D., & Dillon, H.** (1986). The National Acoustic Laboratories' (NAL) new procedure for selecting the gain and frequency response of a hearing aid. *Ear and Hearing, 7*(4), 257–265. <https://doi.org/10.1097/00003446-198608000-00007>
- D'Ascenzo, S., Iani, C., Guidotti, R., Laeng, B., & Rubichi, S.** (2016). Practice-induced and sequential modulations in the Simon task: Evidence from pupil dilation. *International Journal of Psychophysiology, 110*, 187–193. <https://doi.org/10.1016/j.ijpsycho.2016.08.002>
- Donohue, S. E., Liotti, M., Perez, R., III, & Woldorff, M. G.** (2012). Is conflict monitoring supramodal? Spatiotemporal dynamics of cognitive control processes in an auditory Stroop task. *Cognitive, Affective, & Behavioral Neuroscience, 12*(1), 1–15. <https://doi.org/10.3758/s13415-011-0060-z>
- Dosenbach, N. U. F., Visscher, K. M., Palmer, E. D., Miezin, F. M., Wenger, K. K., Kang, H. C., Burgund, E. D., Grimes, A. L., Schlaggar, B. L., & Petersen, S. E.** (2006). A core system for the implementation of task sets. *Neuron, 50*(5), 799–812. <https://doi.org/10.1016/j.neuron.2006.04.031>
- Duthoo, W., Abrahamse, E. L., Braem, S., Boehler, C. N., & Notebaert, W.** (2014). The heterogeneous world of congruency sequence effects: An update. *Frontiers in Psychology, 5*, 1001. <https://doi.org/10.3389/fpsyg.2014.01001>
- Eckstein, M. K., Guerra-Carrillo, B., Singley, A. T. M., & Bunge, S. A.** (2017). Beyond eye gaze: What else can eyetracking reveal about cognition and cognitive development? *Developmental Cognitive Neuroscience, 25*, 69–91. <https://doi.org/10.1016/j.dcn.2016.11.001>
- Egner, T.** (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective, & Behavioral Neuroscience, 7*(4), 380–390. <https://doi.org/10.3758/CABN.7.4.380>
- Erdfelder, E., Faul, F., & Buchner, A.** (1996). GPOWER: A general power analysis program. *Behavior Research Methods, Instruments, & Computers, 28*(1), 1–11. <https://doi.org/10.3758/BF03203630>
- Gendolla, G. H. E., Wright, R. A., & Richter, M.** (2011). Effort intensity: Studies of cardiovascular response. In R. Ryan (Ed.), *The Oxford handbook on motivation* (pp. 420–438). Oxford University Press.
- Gratton, G., Coles, M. G. H., & Donchin, E.** (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General, 121*(4), 480–506. <https://doi.org/10.1037/0096-3445.121.4.480>
- Hyönä, J., Tommola, J., & Alaja, A.-M.** (1995). Pupil dilation as a measure of processing load in simultaneous interpretation and other language tasks. *The Quarterly Journal of Experimental Psychology Section A, 48*(3), 598–612. <https://doi.org/10.1080/14640749508401407>
- Janisse, M. P.** (1977). *Pupillometry: The psychology of the pupillary response*. Hemisphere Publishing.
- Kahneman, D., & Beatty, J.** (1966). Pupil diameter and load on memory. *Science, 154*(3756), 1583–1585. <https://doi.org/10.1126/science.154.3756.1583>
- Kerns, J. G., Cohen, J. D., MacDonald, A. W., III, Cho, R. Y., Stenger, V. A., & Carter, C. S.** (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303*(5660), 1023–1026. <https://doi.org/10.1126/science.1089910>
- Knight, S., & Heinrich, A.** (2017). Different measures of auditory and visual Stroop interference and their relationship to speech intelligibility in noise. *Frontiers in Psychology, 8*, 230. <https://doi.org/10.3389/fpsyg.2017.00230>
- Koelewijn, T., Zekveld, A. A., Festen, J. M., & Kramer, S. E.** (2012). Pupil dilation uncovers extra listening effort in the presence of a single-talker masker. *Ear and Hearing, 33*(2), 291–300. <https://doi.org/10.1097/AUD.0b013e3182310019>
- Kramer, S. E., Kapteyn, T. S., Festen, J. M., & Kuik, D. J.** (1997). Assessing aspects of auditory handicap by means of pupil dilation. *Audiology, 36*(3), 155–164. <https://doi.org/10.3109/00206099709071969>
- Laeng, B., Ørbo, M., Holmlund, T., & Miozzo, M.** (2011). Pupilary Stroop effects. *Cognitive Processing, 12*(1), 13–21. <https://doi.org/10.1007/s10339-010-0370-z>
- Mayr, U., Awh, E., & Laurey, P.** (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience, 6*(5), 450–452. <https://doi.org/10.1038/nn1051>
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D.** (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. <https://doi.org/10.1006/cogp.1999.0734>
- Oh, J., Han, M., Peterson, B. S., & Jeong, J.** (2012). Spontaneous eyeblinks are correlated with responses during the Stroop task. *PLOS ONE, 7*(4), e34871. <https://doi.org/10.1371/journal.pone.0034871>
- Ohlenforst, B., Zekveld, A. A., Lunner, T., Wendt, D., Naylor, G., Wang, Y., Versfeld, N. J., & Kramer, S. E.** (2017). Impact of stimulus-related factors and hearing impairment on listening effort as indicated by pupil dilation. *Hearing Research, 351*, 68–79. <https://doi.org/10.1016/j.heares.2017.05.012>
- Peelle, J. E.** (2018). Listening effort: How the cognitive consequences of acoustic challenge are reflected in brain and behavior. *Ear and Hearing, 39*(2), 204–214. <https://doi.org/10.1097/AUD.0000000000000494>
- Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W., Humes, L. E., Lemke, U., Lunner, T., Matthen, M., Mackersie, C. L., Naylor, G., Phillips, N. A., Richter, M., Rudner, M., Sommers, M. S., Tremblay, K. L., & Wingfield, A.** (2016). Hearing impairment and cognitive energy: The Framework for Understanding Effortful Listening (FUEL). *Ear and Hearing, 37*, 5S–27S. <https://doi.org/10.1097/AUD.0000000000000312>
- Plomp, R., & Mimpen, A. M.** (1979). Improving the reliability of testing the speech reception threshold for sentences. *Audiology, 18*(1), 43–52. <https://doi.org/10.3109/00206097909072618>

- Richter, M., Friedrich, A., & Gendolla, G. H.** (2008). Task difficulty effects on cardiac activity. *Psychophysiology*, *45*(5), 869–875. <https://doi.org/10.1111/j.1469-8986.2008.00688.x>
- Richter, M., Gendolla, G. H. E., & Wright, R. A.** (2016). Three decades of research on motivational intensity theory: What we have learned about effort and what we still don't know. In A. J. Elliot (Ed.), *Advances in motivation science* (Vol. 3, pp. 149–186). Elsevier. <https://doi.org/10.1016/bs.adms.2016.02.001>
- Roberts, K. L., & Hall, D. A.** (2008). Examining a supramodal network for conflict processing: A systematic review and novel functional magnetic resonance imaging data for related visual and auditory Stroop tasks. *Journal of Cognitive Neuroscience*, *20*(6), 1063–1078. <https://doi.org/10.1162/jocn.2008.20074>
- Rondeel, E. W. M., van Steenbergen, H., Holland, R. W., & van Knippenberg, A.** (2015). A closer look at cognitive control: Differences in resource allocation during updating, inhibition and switching as revealed by pupillometry. *Frontiers in Human Neuroscience*, *9*, 494. <https://doi.org/10.3389/fnhum.2015.00494>
- Scherbaum, S., Fischer, R., Dshemuchadse, M., & Goschke, T.** (2011). The dynamics of cognitive control: Evidence for within-trial conflict adaptation from frequency-tagged EEG. *Psychophysiology*, *48*(5), 591–600. <https://doi.org/10.1111/j.1469-8986.2010.01137.x>
- Schmidtke, J.** (2018). Pupillometry in linguistic research: An introduction and review for second language researchers. *Studies in Second Language Acquisition*, *40*(3), 529–549. <https://doi.org/10.1017/S0272263117000195>
- Sirois, S., & Brisson, J.** (2014). Pupillometry. *WIREs: Cognitive Science*, *5*(6), 679–692. <https://doi.org/10.1002/wcs.1323>
- Stroop, J. R.** (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643–662. <https://doi.org/10.1037/h0054651>
- Tai, Y., & Husain, F. T.** (2019). The role of cognitive control in tinnitus and its relation to Speech-in-Noise performance. *Journal of Audiology & Otology*, *23*(1), 1–7. <https://doi.org/10.7874/jao.2018.00409>
- Vaden, K. I., Jr., Kuchinsky, S. E., Ahlstrom, J. B., Dubno, J. R., & Eckert, M. A.** (2015). Cortical activity predicts which older adults recognize speech in noise and when. *Journal of Neuroscience*, *35*(9), 3929–3937. <https://doi.org/10.1523/JNEUROSCI.2908-14.2015>
- Vaden, K. I., Jr., Kuchinsky, S. E., Ahlstrom, J. B., Teubner-Rhodes, S. E., Dubno, J. R., & Eckert, M. A.** (2016). Cingulo-opercular function during word recognition in noise for older adults with hearing loss. *Experimental Aging Research*, *42*(1), 67–82. <https://doi.org/10.1080/0361073X.2016.1108784>
- Vaden, K. I., Jr., Kuchinsky, S. E., Cuta, S. L., Ahlstrom, J. B., Dubno, J. R., & Eckert, M. A.** (2013). The cingulo-opercular network provides word-recognition benefit. *Journal of Neuroscience*, *33*(48), 18979–18986. <https://doi.org/10.1523/JNEUROSCI.1417-13.2013>
- van der Wel, P., & van Steenbergen, H.** (2018). Pupil dilation as an index of effort in cognitive control tasks: A review. *Psychonomic Bulletin & Review*, *25*(6), 2005–2015. <https://doi.org/10.3758/s13423-018-1432-y>
- van Steenbergen, H., & Band, G. P. H.** (2013). Pupil dilation in the Simon task as a marker of conflict processing. *Frontiers in Human Neuroscience*, *7*, 215. <https://doi.org/10.3389/fnhum.2013.00215>
- van Steenbergen, H., Band, G. P. H., & Hommel, B.** (2015). Does conflict help or hurt cognitive control? Initial evidence for an inverted U-shape relationship between perceived task difficulty and conflict adaptation. *Frontiers in Psychology*, *6*, 974. <https://doi.org/10.3389/fpsyg.2015.00974>
- Wang, Y., Naylor, G., Kramer, S. E., Zekveld, A. A., Wendt, D., Ohlenforst, B., & Lunner, T.** (2018). Relations between self-reported daily-life fatigue, hearing status, and pupil dilation during a speech perception in noise task. *Ear and Hearing*, *39*(3), 573–582. <https://doi.org/10.1097/AUD.0000000000000512>
- Zekveld, A. A., Heslenfeld, D. J., Johnsrude, I. S., Versfeld, N. J., & Kramer, S. E.** (2014). The eye as a window to the listening brain: Neural correlates of pupil size as a measure of cognitive listening load. *NeuroImage*, *101*, 76–86. <https://doi.org/10.1016/j.neuroimage.2014.06.069>
- Zekveld, A. A., Koolewijn, T., & Kramer, S. E.** (2018). The pupil dilation response to auditory stimuli: Current state of knowledge. *Trends in Hearing*, *22*, 2331216518777174. <https://doi.org/10.1177/2331216518777174>
- Zekveld, A. A., & Kramer, S. E.** (2014). Cognitive processing load across a wide range of listening conditions: Insights from pupillometry. *Psychophysiology*, *51*(3), 277–284. <https://doi.org/10.1111/psyp.12151>
- Zekveld, A. A., Kramer, S. E., & Festen, J. M.** (2010). Pupil response as an indication of effortful listening: The influence of sentence intelligibility. *Ear and Hearing*, *31*(4), 480–490. <https://doi.org/10.1097/AUD.0b013e3181d4f251>
- Zekveld, A. A., Kramer, S. E., & Festen, J. M.** (2011). Cognitive load during speech perception in noise: The influence of age, hearing loss, and cognition on the pupil response. *Ear and Hearing*, *32*(4), 498–510. <https://doi.org/10.1097/AUD.0b013e31820512bb>
- Zekveld, A. A., van Scheepen, J. A. M., Versfeld, N. J., Veerman, E. C. I., & Kramer, S. E.** (2019). Please try harder! The influence of hearing status and evaluative feedback during listening on the pupil dilation response, saliva-cortisol and saliva alpha-amylase levels. *Hearing Research*, *381*, 107768. <https://doi.org/10.1016/j.heares.2019.07.005>