Dual-task interference in the assessment of listening effort: results of normal-hearing adults, cochlear implant users and hearing aid users.

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ABSTRACT

Purpose: The purpose of the current study was to assess dual-task interference (i.e., changes between the dual-task and baseline condition) in a listening effort dual-task paradigm in normal-hearing (NH) adults, hearing aid (HA) users, and cochlear implant (CI) users.

Method: Three groups of 31 participants were included: (1) NH adults, (2) HA users, and (3) CI users. The dual-task paradigm consisted of a primary speech understanding task in a quiet condition, and a favourable and unfavourable noise condition, and a secondary visual memory task. Dual-task interference was calculated for both tasks, and participants were classified based on their patterns of interference. Descriptive analyses were established and differences between the three groups were examined.

Results: The descriptive results showed varying patterns of dual-task interference between the three listening conditions. Most participants showed the pattern of visual memory interference (i.e., worse results for the secondary task in the dual-task condition, and no difference for the primary task) in the quiet condition, whereas the pattern of speech understanding priority trade-off (i.e., worse results for the secondary task in the dual-task condition, and better results for the primary task) was most prominent in the unfavourable noise condition. Particularly in HA and CI users this shift was seen. However, the patterns of dual-task interference were not statistically different between the three groups.

Conclusions: Results of this study may provide additional insight into the interpretation of dual-task paradigms for measuring listening effort in diverse participant groups. It highlights the importance of considering both the primary and secondary tasks for accurate interpretation of results.

Keywords: listening effort, dual-task paradigm, attention allocation, dual-task interference

INTRODUCTION

Individuals with hearing loss often indicate that listening is an effortful activity, even when sounds are audible and words are recognized accurately (Hughes et al., 2018; Pichora-Fuller, Kramer, Eckert, Edwards, Hornsby, Humes, Lemke, Lunner, Matthen, Mackersie, et al., 2016). According to the Framework of Understanding Effortful Listening (FUEL), this perceived listening effort may be defined as "the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a task, with listening effort applying more specifically when tasks involve listening" (Pichora-Fuller, Kramer, Eckert, Edwards, Hornsby, Humes, Lemke, Lunner, Matthen, Mackersie, et al., 2016). The high amounts of listening effort in individuals with hearing loss can lead to feelings of stress and tiredness, eventually resulting in quitting to participate in listening activities (Hughes et al., 2018; Mackersie et al., 2015; Pichora-Fuller, Kramer, Eckert, Edwards, Hornsby, Humes, Lemke, Lunner, Matthen, Mackersie, et al., 2016). Hence, an increased listening effort in individuals with hearing loss has a negative impact on social connectedness, well-being, and quality of life (Hughes et al., 2018; Pichora-Fuller, Kramer, Eckert, Edwards, Hornsby, Humes, Lemke, Lunner, Matthen, Mackersie, et al., 2016). Also, hearing aid (HA) users and cochlear implant (CI) users, whose hearing is (partly) restored with their hearing device, experience increased listening effort compared to normal-hearing listeners when tested under the same listening conditions (Alhanbali et al., 2017; Hughes et al., 2018; Perreau et al., 2017). However, results of a study by Hughes and Galvin (2013) demonstrated similar effort in adolescent CI users and normal-hearing listeners, when listening conditions were manipulated to result in similar speech perception scores (Hughes & Galvin, 2013). Consequently, it is suggested to consider listening effort as an important outcome measure in the field of hearing rehabilitation, next to the traditional audiological outcome measures such as pure-tone audiometry and speech audiometry. Currently, there is no standardized test procedure to assess listening effort in clinical practice (Gagne et al., 2017). Diverse methods have been described, which can be divided into three main categories (Francis & Love, 2020; Shields et al., 2023): (1) subjective measures, more specifically self-report, such as validated effort questionnaires and visual analogue scales (VAS) (Alhanbali et al., 2017), (2) physiological measures, such as electroencephalography (EEG), pupillometry and assessments of cortisol level or skin conductance (Bertoli & Bodmer, 2014, 2016; Kestens, Van Yper, et al., 2023; Mackersie et al., 2015; Naylor et al., 2018), and (3) behavioral measures, such as reaction time (Houben et al., 2013) and dual-task paradigms (Gagne et al., 2017). Dual-task paradigms are based on the theory of limited cognitive capacity of Kahneman (1973). Particularly, when a participant is asked to perform two concurrent tasks simultaneously, the processing system will prioritize one of both tasks if the required resources exceed the participant's constrained brain capacity. This results in a decrement in performance in one or both of the tasks, relative to when each task is performed alone (Plummer & Eskes, 2015). In order to measure listening effort, usually, a primary speech understanding task and a secondary competing task are performed both separately (i.e., baseline condition) and simultaneously (i.e., dual-task condition) (Gagne et al., 2017). In literature, a variety of possible secondary tasks has been described. Some of the most commonly used secondary tasks are tactile pattern recognition (e.g. Gosselin and Gagné, 2011), memory tasks (e.g. Degeest et al., 2015; Hornsby, 2013), and probe reaction time tasks (e.g. Desjardins and Doherty, 2013). Typically, listening effort is calculated as the difference in performance on the secondary task between the baseline condition (i.e., when the task is performed separately) and the dual-task condition (i.e., when the task is performed simultaneously with the primary task). Mostly, the listener is instructed to prioritize the primary speech understanding task since it is required that performance for this task is similar for both baseline- and dual-task conditions for reliable interpretation of the results (Gagne et al., 2017). However, it may not always be possible to make sure that this requirement is fulfilled. For example, data obtained from children suggest that the simple instruction to prioritize the primary task may not be sufficient to ensure that the participants will optimize their performance for this task (Choi et al., 2008; Irwin-Chase & Burns, 2000). Besides, the requirement of similar primary task performance between the baseline- and dual-task conditions are mostly evaluated on a group level (e.g. Degeest et al., 2022a, 2022b; Desjardins & Doherty, 2013; Xia et al., 2015), which neglects possible individual differences. To overcome these problems, it is suggested to evaluate the difference in performance between the dual-task- and baseline conditions for both the primary and the secondary task by computing the dual-task effect (DTE) for both tasks (Gagne et al., 2017; Plummer & Eskes, 2015). More specifically, the DTE could be calculated using the following formula: DTE = 100 × [score in dual-task condition - score in baseline condition]/score in baseline condition (Plummer & Eskes, 2015). Thereby, a negative DTE indicates a decrease in performance in the dual-task condition compared to the baseline condition (i.e., dual-task cost), while a positive value represents an improvement in performance (i.e., dual-task benefit) (Plummer & Eskes, 2015; Plummer et al., 2014). The authors suggest that the magnitude and direction of these dual-task effects may be influenced by the interaction between the primary and the secondary tasks, and by how individuals prioritize their attention (Plummer & Eskes, 2015). Therefore, a conceptual framework has been proposed that can be used for classifying patterns of dual-task interference, based on the DTE for both the primary and secondary tasks, providing a complete overview of the participant's performance for the dual-task paradigm (Plummer et al., 2013). Furthermore, it is demonstrated that this approach to measure dual-task interference considers the tradeoffs in performance that the participant may attribute to the primary and the secondary tasks (Plummer & Eskes, 2015).

Given the ecological validity of a dual-task paradigm, it seems a useful and feasible assessment tool for listening effort in clinical practice. A dual-task paradigm can provide additional information over and beyond the traditional audiological outcomes used in clinical practice, and the results can also be valuable for counseling purposes. Dual-task interference is a new way to approach the concept of listening effort by considering the DTE of both the primary and secondary tasks of a dual-task paradigm. Consequently, a deeper understanding regarding dual-task interference and the different attention allocation strategies is necessary.

Therefore, the purpose of the current study was to evaluate dual-task interference in a listening effort dual-task paradigm in normal-hearing individuals, HA users, and CI users. More specifically, the patterns of dual-task interference were compared between these three groups of participants; and these patterns were also compared between different listening conditions with and without background noise. Consequently, more insight can be gained regarding the used attention allocation strategies of individuals with a distinct hearing status in different listening conditions.

MATERIALS AND METHOD

Participants

Three groups of participants were recruited for this study: (1) normal-hearing adults (NH), (2) adults with a moderate to severe hearing loss using HAs (i.e., HA users), and (3) adults with a severe to profound bilateral hearing loss using CI (i.e., CI users). These groups were matched for age, sex, and educational level since these factors were considered to be possible influencing factors for cognition and listening effort (Degeest et al., 2015; Kestens et al., 2021). All participants were native Dutch speakers and had normal or corrected-to-normal vision according to anamnesis and screening with the Near Vision Snellen Eye Chart (Snellen, 1873). Individuals with self-reported learning disorders, attention deficits, or psychiatric or neurological disorders were excluded. Besides, the risk for cognitive impairment was assessed in participants aged 60 years or older using the Montréal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). A cut-off score of 23 was applied for exclusion (Carson et al., 2018). For the HA- and CI users, only experienced users were included (i.e., device usage for at least one year).

Air-conduction pure-tone hearing thresholds were bilaterally obtained for all octave frequencies between 0.25 and 8.00 kHz using the modified Hughson-Westlake method. Pure-tone audiometry was conducted in a sound-attenuated booth using an Equinox Interacoustics 2.0 audiometer. For the NH individuals, stimuli were presented through headphones (TDH39 Audiometric Headphones) for both ears separately. NH participants were included when hearing thresholds at all measured frequencies of the better ear were equal to or better than the fifth percentile for age- and sex-adjusted thresholds norms (International Organization for Standardization (ISO), 2017). For the HA- and CI users, pure-tone audiometry was conducted in an unaided condition using headphones (TDH39 Audiometric

Headphones) for both ears separately, as well as in a best-aided condition in free field (through a frontally placed Kenwood LS-56 loudspeaker). HA- and CI users were included when unaided hearing thresholds revealed a bilateral moderate to severe and severe to profound hearing loss, respectively, according to the classification as provided by the World Health Organization (World Health Organization, 2021b). The best aided condition was chosen to be representative for listening in daily life. More specifically, for the CI users, this could be either with CI only, with both CIs, or with CI in combination with a contralateral HA. For the HA users, the best-aided condition was with both HAs.

All participants filled out an online version of the hearing-related Quality of Life questionnaire for Auditory-VIsual, COgnitive and Psychosocial functioning (hAVICOP) (Ceuleers et al., 2023) to verify if the participants could be considered a representative sample of NH individuals, HA users, and CI users in terms of hearing-related quality of life and device satisfaction. The hAVICOP is a Dutch questionnaire consisting of 35 test items, formulated as statements whereby the participant has to indicate on a VAS how often these statements apply to his/her/them functioning. A score of zero corresponds to ‘rarely or never’, while a score of 100 represents ‘(almost) always’. Three domains regarding the primary outcome, i.e., hearing-related quality of life can be explored using the hAVICOP: (1) auditory-visual functioning, (2) cognitive functioning, and (3) psychosocial functioning. Furthermore, a fourth domain, device satisfaction, is included as a secondary outcome. The items in this domain are only applicable if the recipient is wearing a HA and/or CI. Scores can be calculated for each domain separately, and also a total score for the primary outcome can be calculated. A higher score reflects a lower impact of hearing loss on the hearing-related quality of life.

This study was approved by the local ethical committee. All participants signed an informed consent in accordance with the statements of the declaration of Helsinki.

Test procedure dual-task paradigm

The dual-task paradigm used in the current study was based on the paradigm reported by Degeest et al. (2015). A primary and secondary task were performed separately and simultaneously, further denoted as the baseline condition and dual-task condition, respectively. The primary task consisted of a speech understanding task in different listening conditions. The secondary task was a visual memory task.

Testing was performed in a quiet, non-reverberant room illuminated with standard room- and daylight. At the beginning of each task (i.e., baseline condition for primary- or secondary task, and dual-task condition), both written and verbal instructions were provided to ensure that all participants had a good understanding of the task. A practice trial was presented to ensure that the participants understood the instructions and were familiar with the test procedure.

Primary and secondary task

The primary task was a speech understanding task, in which monosyllabic digits ranging from zero to 12 were used as speech stimuli. All digits were pronounced clearly by a female Dutch-speaking speech- and language therapist and recorded using an external microphone (Samsung C01U PRO) and Praat software at a sampling rate of 44100 Hz. The experiment included three different listening conditions: a quiet condition (without background noise), and two noise conditions, with noise levels set at signal-to-noise ratio (SNR) +4 dB (favourable noise condition) and SNR -6 dB (unfavourable noise condition). For each listening condition, three series of five randomly selected digits were presented with a one second interstimulus interval. Afterwards, the participants were asked to verbally repeat the series of digits. The listening conditions were presented in increasing difficulty to promote motivation: first the quiet condition followed by the favourable and the unfavourable noise condition. For the noise conditions, a steady-state noise which was spectrally shaped to reflect the long-term average speech spectrum of the speech material was used. Prior to stimulus onset (i.e., presentation of the first digit of the series), 10 s noise followed by a 1 s pure-tone of 1000 Hz were included to allow the participant to adapt to the noise and to focus the attention on the stimulus presentation. The digits and background noise were presented through a frontally placed loudspeaker at a distance of 90 cm from the participant (type Bose Companion 2 Series III). The equipment was calibrated using a 2250-B Bruël en Kjaer real time sound analyzer (Brüel & Kjær, Denmark) so that the intensity of the noise was fixed at 65 dB SPL.

The secondary task was a visual memory task. Thereby, a raster consisting of 12 separated squares was presented on a white computer screen (type Dell P2419H, size 24 inches) at maximum brightness. An example of this raster can be found in Degeest et al. (2015). The screen was placed at eye level at a distance of approximately 70 cm from the participant. Within this raster, a series of five identical blue-filled circles appeared for 1 second with an interstimulus interval of 1 second. Participants were instructed to memorize the positions of these circles in the raster and to indicate these positions after each series of five on a score form, presented on a tablet. Thereby, it was obligated to indicate five squares, even if guessing was necessary.

Dual-task procedure

Firstly, the primary and the secondary tasks were presented separately in the baseline condition. For the primary task, a raw word score was calculated based on the total amount of correctly repeated digits, resulting in a maximum score of 15 for each listening condition. For the secondary task, five trials of five circles were presented in quiet. A raw score was calculated based on the amount of correctly indicated squares. The baseline values for the secondary task were determined by using only the last two trials to control for learning effects (Degeest et al., 2015). To determine the score on 15, the score on ten was multiplied by 1.5.

Secondly, both tasks were performed simultaneously in the dual-task condition. In this condition, three trials of five digits together with five circles appearing on the raster were presented in the quiet condition as well as in the favourable and unfavourable noise conditions. The start of the auditory presentation of a digit and the start of appearance of a circle were not exactly simultaneous in order to avoid a conditioning effect. Participants were instructed to prioritize the primary speech understanding task (Gagne et al., 2017). The scoring procedures for both the primary- and secondary tasks in the dual-task condition were identical as described above for the baseline conditions.

For each participant the dual-task interference was quantified by calculating the DTE for both the primary and the secondary task separately (DTE = 100 × [score in dual-task condition - score in baseline condition]/score in baseline condition) (Plummer & Eskes, 2015). The DTE represents the relative change in performance in the dual-task condition compared to the baseline condition, with a negative DTE (i.e., - DTE) indicating a dual-task cost, while a positive value (i.e., + DTE) represents a dual-task benefit (Plummer & Eskes, 2015; Plummer et al., 2014). Then, patterns of dual-task interference were examined based on the conceptual framework as described Plummer et al. (2013, 2014, 2015), by plotting the DTE of the primary and secondary task against each another. As shown in Figure 1, nine distinct patterns can be distinguished: (1) Speech understanding priority trade off (+ DTE in speech understanding task, - DTE in visual memory task), (2) Mutual facilitation (+ DTE in both tasks), (3) Visual memory priority trade off (+DTE in visual memory task, - DTE in speech understanding task), (4) Mutual interference (- DTE in both tasks), (5) Visual memory facilitation (zero DTE in speech understanding task, +DTE in visual memory task), (6) Visual memory interference (zero DTE in speech understanding task, -DTE in visual memory task), (7) Speech understanding facilitation (zero DTE in visual memory task, +DTE in speech understanding task), (8) Speech understanding interference (zero DTE in visual memory task, -DTE in speech understanding task), and (9) No interference (zero DTE in both tasks). Based on these patterns it would be possible to identify underlying attentional strategies or participants' preferences in particular dual-task situations (Plummer & Eskes, 2015).

Statistical analysis

Statistical analysis was performed using SPSS Version 28 (SPSS Inc.). Firstly, descriptive parameters and normality statistics were established for the participants' characteristics (e.g. age, sex, educational level, duration of hearing loss), the hAVICOP, and all parameters related to the dual-task paradigm. Secondly, the differences between the three groups of participants (i.e., NH individuals, HA users, and CI users) were assessed for all these variables. For normally distributed continuous variables, a one-way ANOVA was conducted, with the assumption of homogeneity of variances being tested by Levene's Test of Homogeneity of Variance. If this assumption was met ($p > 0.05$), and the ANOVA showed statistically significant results, further analysis was done using Tukey post hoc tests. However, if the assumption of homogeneity of variances was violated ($p < 0.05$), one-way Welch's ANOVA was conducted instead, and if significant, Games-Howell post hoc tests were performed for further analysis. The other assumptions for ANOVA (no outliers, and independence of observation) were met for all analyses. For non-normally distributed continuous variables, the Kruskal-Wallis test was utilized. If the Kruskal-Wallis test revealed statistically significant results, pairwise comparisons were performed using Dunn's (1964) procedure, with a Bonferroni correction for multiple comparisons. For the categorical variables, more specifically for the patterns of dual-task interference, a Fisher's exact test was used to assess if there was an association between these patterns and the group to which a participant belongs (i.e., NH individual, HA users, or CI user). Lastly, the effects of different listening conditions and different groups on the type of dual-task interference were estimated with a logistic generalized estimating equations (GEE) model, taking into account the correlation between measurements nested within participants. In the GEE model participant was included as id, correlation structure was "exchangeable", and group, listening condition and their interaction were included as predictor variables. Therefore, a new variable was created, which was equal to one if the participant showed the pattern of 'Visual memory interference', and which was equal to zero if another pattern was shown. The rationale for considering this pattern was that it was expected to be the most frequent pattern, since the instruction was given to prioritize the primary speech understanding task in the dual-task condition.

RESULTS

Participants

A total of 93 participants took part in this study, with 31 participants in each of the three groups: (1) NH adults, (2) HA users, and (3) CI users. Table 1 shows detailed descriptions of age, sex, educational level, and hearing sensitivity for all participants, as well as hearing- and device-related factors for the HA- and CI users, and the statistical results of the differences for these factors between the three groups. Note that the duration of hearing loss was found to be significantly different for the HA- and

CI users. In the group of CI users, eight participants had a prelingually acquired hearing loss; the other 23 participants had a postlingually acquired hearing loss. All included CI users with a prelingually acquired hearing loss had used HAs in combination with an oral-aural communication strategy prior to implantation, and no one used sign language as a (primary) communication strategy. Consequently, it was decided to consider the CI users with both post- and prelingual onset hearing loss as one group. Figure 2 shows the mean (unaided) air-conduction hearing thresholds of participants' better ear per group at each tested frequency.

Table 2 presents the descriptive results for the hAVICOP per group and the results of the differences between the three groups. For the primary outcome, results revealed a statistical difference ($p < 0.05$) between the groups for all domains (i.e., auditory-visual functioning, cognitive functioning, and psychosocial functioning) and the total score. Post hoc testing showed that the NH individuals scored significantly higher for the three domains and the total score compared to the HA users ($p < 0.001$ for all domains and the total score) and CI users ($p < 0.001$ for all domains and the total score). For the primary outcome, there was no significant difference between the HA users and CI users ($p > 0.05$). For the secondary outcome device satisfaction, the CI users scored significantly higher than the HA users ($p = 0.008$).

Dual-task paradigm

Primary and secondary task

Results of the primary and secondary tasks in the baseline- and dual-task conditions are shown in Figures 3 and 4, respectively. Supplemental Digital Contents 1 and 2 provide exact descriptive (mean, SD, median, and range) and statistical results.

It can be seen that the speech understanding scores for the primary task decrease with increasing difficulty of the listening condition (Figure 3). For the primary speech understanding task in the baseline condition, significant differences between the three groups were found for both noise conditions ($\chi2(2) = 15.53$, $p < 0.001$ for the favourable noise condition, and $F(2, 55.80) = 93.06$, $p <$

0.001 for the unfavourable noise condition). More specifically, NH individuals scored significantly better in the favourable and the unfavourable noise conditions than the HA users ($p = 0.006$ for the favourable noise condition, and $p < 0.001$ for unfavourable noise condition) and CI users ($p = 0.001$ for favourable noise condition, and $p < 0.001$ for unfavourable noise condition). Results in the quiet condition were not significantly different between the three groups ($\chi2(2) = 5.01$, $p = 0.082$). In the dual-task conditions, the results are similar to those of the baseline condition. More specifically, significantly different scores were found for both noise conditions ($\chi2(2) = 7.92$, $p = 0.019$ for the favourable noise condition, and $F(2, 88) = 55.07$, $p < 0.001$ for the unfavourable noise condition), and not in the quiet condition ($\chi2(2) = 1.75$, $p = 0.416$). The NH individuals scored significantly better than the CI users ($p = 0.023$) in the favourable noise condition. In the unfavourable noise condition, the NH individuals' scores were significantly better compared to both the HA users ($p < 0.001$) and the CI users ($p < 0.001$).

For the secondary visual memory task, rather high scores (mean score > 60% for all conditions) are observed, in general (Supplemental Material 2). It can be observed that scores in the baseline condition are descriptively higher than in the dual-task condition (Figure 4). In the baseline condition no significant differences were demonstrated across groups ($\chi2(2) = 2.06$, $p = 0.357$). In the dual-task condition, there was no significant differences across groups for the secondary task in the quiet condition ($F(2, 90) = 1.87$, $p = 0.160$) and in the unfavourable noise condition ($F(2, 88) = 0.86$, $p = 0.429$). In the favourable noise condition, the one-way ANOVA revealed a significant result ($F(2, 90) = 3.33$, $p = 0.040$). However, post hoc testing was not significant.

Dual-task effect

Figure 5 presents results for the DTE for both the primary speech understanding task and the secondary visual memory task per listening condition. Supplemental Digital Content 3 provides exact descriptive (mean, SD, median, and range) and statistical results. Considering the primary task, a trend can be seen with low mean values for the DTE, indicating a small change in performances between the dual-task-and baseline conditions, for the quiet condition and the favourable noise condition, especially for the HA users and CI users. In the unfavourable noise condition a positive mean DTE was found for the HA and CI users, indicating a dual-task benefit. The median for the DTE of the primary task is zero for all listening conditions for all groups, except for the CI users in the unfavourable noise condition. The Kruskal-Wallis test showed a significant result for the primary task in the unfavourable noise condition ($\chi2(2) = 9.61$, $p = 0.008$), with significant higher DTE values for the CI users compared to the NH individuals ($p = 0.002$). For the other listening conditions no significant differences were found between the three groups ($F(2, 90) = 0.83$, $p = 0.441$ for the quiet condition, and $\chi2(2) = 2.87$, $p = 0.238$ for the favourable noise condition). Considering the secondary task, it can be seen that the mean and the median of the DTE were negative for all conditions for all groups, indicating a dual-task cost (Figure 5b). No significant differences were found between the three groups for all listening conditions ($F(2, 90) = 1.19$, $p = 0.308$ for the quiet condition; $F(2, 90) = 1.50$, $p = 0.229$ for the favourable noise condition; $F(2, 88) = 1.08$, $p = 0.343$).

Patterns of dual-task interference

In Table 3, the distribution of the participants over the different patterns of dual-task interference is displayed per listening condition. Also, in Figure 6 these results are illustrated based on the conceptual framework as described by Plummer et al. (2013, 2014). As can be seen in Table 3 and Figure 6, in the quiet condition, the largest number of the participants, both when considering the total group as well as in the subgroups (i.e., NH, HA users, and CI users), exhibited the pattern of Visual memory interference (48.4%), followed by Mutual interference (33.33%). The Fisher's exact test showed no significant association between the pattern of DTE and the group to which the participants belong ($p = 0.247$). In the favourable noise condition, the pattern of Visual memory interference was the most commonly seen pattern for the total group (36.6%). However, there was also an increased proportion of the total group of participants (17.2%) that exhibited the pattern of Speech understanding priority trade off, especially in the group of CI users this trend was seen. Besides, the pattern of Mutual interference was seen in another 16.1% of the total group of participants. No significant association was found between the pattern of DTE in the favourable noise condition and the group to which the participants belong (p = 0.115). In the unfavourable noise condition, the largest number of participants exhibited the pattern of Speech understanding priority trade off when considering the total group (46.2%). Especially for the HA users and the CI users, it can be observed that most of them showed this pattern (45.2% and 61.3%, respectively). The patterns of Mutual Interference and Visual memory interference were the other two most common categories for the total group, containing 27.5% and 20.9% of the participants, respectively. Considering the NH individuals, most of them demonstrated the pattern of Mutual interference. However, the Fisher's exact test showed no significant association between the pattern of DTE and the group where the participants belong to (p = 0.061).

Lastly, the GEE model showed a statistically significant effect of listening condition for the pattern of 'Visual memory interference' (p = 0.001). Pairwise comparisons revealed a significant difference between the quiet condition and the unfavourable noise conditions (p < 0.001), and between the favourable noise conditions and the unfavourable noise condition (p = 0.008), with the pattern of 'Visual memory interference' being significantly less common in the unfavourable noise condition. The estimated means are 0.48 (95% confidence interval ranging from 0.38 to 0.59), 0.36 (95% confidence interval ranging from 0.27 to 0.47), and 0.20 (95% confidence interval ranging from 0.13 to 0.30), for the quiet condition, the favourable noise condition, and the unfavourable noise condition, respectively. No significant effect was observed for group (p = 0.130).

DISCUSSION

The aim of this study was to evaluate dual-task interference in a listening effort dual-task paradigm in normal-hearing individuals, HA users, and CI users.

Patterns of dual-task interference were determined by considering the results of the DTE of the primary and secondary task together, as in the conceptual framework of Plummer et al. (2014). These patterns can be an indication of a person's preferred attention allocation strategy and whether they maintain stable performance in the primary task across baseline and dual-task conditions, a requirement to calculate listening effort following the traditional approach. In several previous studies using this traditional approach, this requirement of stable performance in the primary task was fulfilled (e.g. Degeest et al., 2022a, 2022b; Desjardins & Doherty, 2013; Xia et al., 2015). In other studies, a difference between the baseline- and dual-task conditions was found for the primary task, but despite this finding, listening effort was still assessed by considering only the difference in performance between the baseline- and dual-task conditions in the secondary task (Abdel-Latif & Meister, 2022; Fraser et al., 2010). In all of these studies, this difference between the baseline- and dual-task conditions for the primary task were evaluated on a group level, which neglects possible individual differences. In the current study, the patterns of dual-task interference were determined at an individual level. Most participants did not demonstrate a pattern where primary speech understanding task performance remained stable across baseline and dual-task conditions (i.e., Visual memory interference, Visual memory facilitation, and No interference). This finding was observed despite providing instructions to prioritize the primary speech understanding task in the dual-task conditions, indicating that the traditional approach, in which only the secondary task is considered, is insufficient for an adequate interpretation.

Moreover, in more challenging listening conditions, fewer individuals showed these patterns with stable performance for the primary task. In the unfavourable noise condition, most of the participants, particularly HA users and CI users, even demonstrated the pattern of Speech understanding priority trade off, indicating a dual-task benefit for the primary speech understanding task and a dual-task cost for the secondary task. This trend was rather unexpected. Other studies in which a difference was found for the primary speech understanding task between the baseline- and dual-task conditions mostly observed a dual-task cost for the primary task (Abdel-Latif & Meister, 2022; Fraser et al., 2010). Notwithstanding, a dual-task benefit on the primary task was also seen in previous research in children (Choi et al., 2008).

One possible explanation for this trend could be the explicit instruction to prioritize the primary speech understanding task in the dual-task condition. In the baseline condition, no comparable focus was put on the primary speech understanding task. As a result, perhaps participants tried harder to perform well for the speech understanding task in the dual-task condition than in the baseline condition. However, in the study of Choi et al. (2008) the effect of different priority instructions was investigated, and it was found that regardless of task priority, the children in both groups showed the same patterns in the dual-task condition. This suggests that instructions given to participants on how to prioritize are ineffective, and do not significantly affect the attention allocation strategy, and consequently the patterns of dual-task interference. However, possibly, the results of Choi et al. (2008) found in children can not be generalized for the adult population. Currently, the effect of prioritization instruction in adults is being investigated (Kestens et al., In preparation).

Another possible explanation for the increasing number of participants demonstrating a dual-task benefit for the primary speech understanding task could be that the appearance of the blue-filled circles of the secondary memory task simultaneously with the presentation of the digits of the primary task gives an additional visual attention cue. Despite the small asynchrony between the start of the presentation of a digit and the start of the appearance of a circle, this additional visual cue may have been particularly useful in the unfavourable noise condition (with an SNR of -6 dB) as a hint for participants to focus on the digits. Additionally, the 1 s pure-tone that announced the start of the speech stimuli in the noise conditions may have been an additional cue that influenced attention.

It is also possible that participants may have allocated more resources to the primary speech understanding task when the listening conditions became harder due to more background noise, explaining why this dual-task benefit for the primary task was most apparent in the noise conditions. Kahneman (1973) describes that subjects can provide more attention when task difficulty is increased. It is hypothesised that the effort invested in a task is mainly determined by the intrinsic demands of the task, and that voluntary control over effort is quite limited (Kahneman, 1973). This is consistent with the Framework for Understanding Effortful Listening (FUEL), stating that the amount of listening effort is influenced by the difficulty of the listening condition and the participants' motivation (Pichora-Fuller, Kramer, Eckert, Edwards, Hornsby, Humes, Lemke, Lunner, Matthen, & Mackersie, 2016). Listeners typically expend more resources as auditory input is more degraded (e.g. due to more background noise, or due to listening through a HA or CI) until the acoustic challenge becomes too difficult, at which point effort decreases (Peelle, 2018). So, it is possible that participants, and HA- and CI users in particular, were more attentive and more motivated to perform well, leading them to exert an extra effort in understanding the speech stimuli during the dual-task condition, especially in the unfavourable noise condition. They could expect that the task would be difficult, but not too difficult, based on the previous conditions.

Lastly, it's worth noting that the unfavourable noise condition in the dual-task condition was the final task for participants, which might have influenced the results. The fixed presentation order could have led to a learning effect or task-related fatigue, potentially resulting in better or worse performance in the final task of the test protocol, respectively. For future research, it is suggested to randomize the order of the different listening conditions, and the baseline- and dual-task conditions to rule out any order effect, unless there is a specific reason not to do so, as in the current study.

Strengths, limitations and future perspectives

The current study was unique in its kind because it is, to the best of our knowledge, the first to implement Plummer's conceptual framework of dual-task interference (Plummer et al., 2014) within audiological research on listening effort. The results of this study provide essential information for adequate interpretation of dual-task paradigms for measuring listening effort, specifically by evaluating dual-task interference. It is suggested not to consider this dual-task interference as a direct measure for listening effort, but it could offer a deeper understanding of changes in attention allocation. The indication of a person's preferred attention allocation strategy, could be very valuable information. Speech understanding in daily life occurs often in combination with other tasks, so information regarding an individual's ability dual-task performances could be useful for counseling and/or to take into account during auditory training.

This study included three groups of participants with a distinct hearing status: NH individuals, HA users and CI users. All participants' scores in the different subdomains and the total score of the hAVICOP align with the scores reported in the original validation study by Ceuleers et al. (2023) and the study by Kestens, Keppler, et al. (2023) on the effect of age on hearing-related quality of life, measured with the hAVICOP. This suggests that the participants in the current study are not outliers in terms of their subjective experience of hearing-related quality of life and device satisfaction, making them a representative sample of NH individuals, HA users, and CI users. The groups of participants were matched very well based on sex, age, and educational level. Nonetheless, it is possible that there could be other influencing factors that were not taken into account (e.g. self-efficacy, language ability, the presence of tinnitus) since listening effort is considered a complex multidimensional concept (Peelle, 2018). For example, individuals with higher self-efficacy are more likely to allocate more cognitive resources to conduct a task compared to those with lower self-efficacy (Pichora-Fuller, Kramer, Eckert, Edwards, Hornsby, Humes, Lemke, Lunner, Matthen, & Mackersie, 2016). Self-efficacy is defined as an individual’s confidence in their own ability to successfully perform a task (Bandura, 2010), and it determines, among other things, individuals’ motivation. Consequently, implementing an assessment of motivation seems an added value in the research regarding listening effort (Peelle, 2018; Pichora-Fuller, Kramer, Eckert, Edwards, Hornsby, Humes, Lemke, Lunner, Matthen, & Mackersie, 2016). However, such assessment was not included in the current study.

Besides, the NH individuals scored significantly better than the HA- and CI users for the primary speech understanding task, in both the favourable and unfavourable noise conditions, both in baseline- and dual-task conditions. The only exception was in the dual-task condition with favourable noise, where NH individuals had significantly better scores than CI users, and no significant difference was observed between NH individuals and HA users. For the quiet condition, the scores of the three groups were not significantly different. This is in accordance with the frequently reported difficulties with speech understanding in noise by HA users and CI users, while results for speech understanding in quiet are good (Fetterman & Domico, 2002; Fu & Nogaki, 2005; Löhler et al., 2015; Lopez-Poveda et al., 2017; Zhao et al., 2008). However, these differences in speech understanding performances might have influenced the dual-task interference results. In future research, it could be interesting to compare the results of normal-hearing individuals and individuals with hearing loss when equal performance on speech understanding is considered (e.g., an SNR where 80% speech understanding is reached) instead of using fixed listening conditions.

Furthermore, future research will focus on the effect of the instruction to prioritize a specific task (Kestens et al., In preparation). Also, the possibilities to determine treatment effects after, for example, cochlear implantation, hearing aid use and/or auditory training, using this approach for dual-task paradigms should be explored. It is suggested that the representation of an individual's dual-task performance using the conceptual framework provided by Plummer et al. (2014) could also be a useful tool for counseling of patients who experience specific difficulties with speech understanding when conducting another competing task simultaneously, leading to increased listening effort.

Conclusion

This study examined the dual-task effect and patterns of dual-task interference in a dual-task paradigm for measuring listening effort in NH individuals, HA users, and CI users. The majority of participants did not demonstrate stable performance for the primary task in both baseline- and dual-task conditions, indicating that the traditional approach of measuring listening effort may be insufficient. A large number of participants, especially HA users and CI users, showed a dual-task benefit for the primary speech understanding task, particularly in the unfavourable noise condition. This finding suggests that participants may allocate more resources and make extra effort to understand the speech stimuli in difficult listening conditions. However, the causes and implications of this trend, need to be explored further. Overall, this study provides valuable insights into the interpretation of dual-task paradigms for measuring listening effort.

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Data Availability Statement: The datasets generated during and/or analyzed during the current study are not publicly available due to ethical restrictions. The participants in this study did not give consent to make data publicly available.

TABLES

Table 1: participant characteristics per group (n = 93).

Characteristics	**NH (n = 31)**	**HA users (n = 31)**	**CI users (n = 31)**	**Results**	
				Test statistic	*p*
Gender				N/A	
Male	10 (32.3%)	10 (32.3%)	10 (32.3%)		
Female	21 (67.7%)	21 (67.7%)	21 (67.7%)		
Age (mean (yrs) and SD)	58.76 (14.49)	59.31 (14.06)	58.86 (14.28)	F(2, 90) = 0.013	0.987
Educational level: years of education (mean (yrs) and SD)	14.42 (2.13)	14.03 (2.06)	13.90 (2.60)	F(2, 90) = 0.433	0.650
Hearing sensitivity: better ear $PTA_{0.5, 1, 2, \text{and } 4 \text{ kHz}}$ in unaided condition (mean (dB HL) and SD)	10.08 (8.23)	56.37 (12.29)	91.61 (12.98)	F(2, 57.23) = 471.35	< 0.001
Duration of hearing loss (mean (yrs) and SD)	N/A	23.61 (15.32)	32.35 (16.54)	F(1, 60) = 4.66	0.035
Cause of hearing loss	N/A			N/A	
Meniere’s disease		3 (9.7%)	3 (9.7%)		
Otosclerosis		1 (3.2%)	4 (12.9%)		
(Potentially) genetic		14 (45.2%)	7 (22.6%)		
Age-related hearing loss		1 (3.2%)	0 (0.0%)		
Syndromic hearing loss		3 (9.7%)	1 (3.2%)		
Cholesteatoma		4 (12.9%)	1 (3.2%)		
Trauma		0 (0.0%)	2 (6.5%)		
Unknown		4 (12.9%)	12 (38.7%)		
Others		1 (3.2%)	1 (3.2%)		
Fitting	N/A			N/A	
Unilateral CI - non bimodal		N/A	8 (25.8%)		
Unilateral CI - bimodal		N/A	20 (64.5%)		
Bilateral CI		N/A	3 (9.7%)		

Bilateral HA		31 (100.0%)	N/A	
Device (HA and/or CI) use per day	N/A			N/A
0-4 hr		0 (0.0%)	0 (0.0%)	
5-9 hr		5 (16.1%)	0 (0.0%)	
10-12 hr		3 (9.7%)	4 (12.9%)	
13-16 hr		21 (67.7%)	26 (83.9%)	
> 16 hr		2 (6.5%)	1 (3.2%)	

Note: yrs, years; SD, standard deviation; N/A, not applicable; bimodal, CI and contralateral HA; PTA, Pure Tone Average; HL, Hearing Level; Device use per day was based on subjective estimation of the participant in anamnesis

Table 2: Descriptive data per group (NH, HA users, and CI users) and results for Kruskall – Wallis for the hAVICOP

Variable	**NH**			**HA users**			**CI users**			**Results**	
	Mean (SD)	Median	Range	Mean (SD)	Median	Range	Mean (SD)	Median	Range	Test Statistic	*p*
Primary outcome											
Auditory-visual functioning	90.87 (9.57)	94.42	67.58-99.50	50.24 (19.21)	55.00	12.92-80.17	48.26 (15.58)	48.50	14.25-87.33	$\chi2(2) = 57.45$	< 0.001
Cognitive functioning	78.14 (25.35)	87.00	17.67-99.50	53.49 (22.15)	47.83	3.17-93.67	57.78 (16.56)	60.67	21.00-87.00	$\chi2(2) = 19.86$	< 0.001
Psychosocial functioning	94.88 (8.74)	98.89	66.44-99.89	49.84 (21.30)	48.67	8.44-96.22	60.60 (20.77)	65.78	27.33-97.89	$\chi2(2) = 54.41$	< 0.001
Total score	89.38 (10.66)	93.59	58.11-99.33	50.83 (17.17)	48.30	9.26-82.56	54.49 (14.66)	54.41	28.15-82.74	$\chi2(2) = 54.85$	< 0.001
Secondary outcome											
Device satisfaction	N/A	N/A	N/A	61.19 (18.18)	62.50	18.00-99.00	71.21 (17.74)	72.88	11.38-93.63	$\chi2(1) = 6.93$	0.008

Note: N/A, not applicable

Table 3: Frequency table of patterns of dual-task interference

		Speech priority trade off	Mutual facilitation	Visual memory priority trade off	Mutual interference	Visual memory facilitation	Visual memory interference	Speech facilitation	Speech interference	No interference
Quiet condition	NH (n=31)	1 (3.2%)	0 (0.0%)	2 (6.5%)	9 (29.0%)	0 (0.0%)	18 (58.1%)	0 (0.0%)	1 (3.2%)	0 (0.0%)
	HA users (n=31)	5 (16.1%)	0 (0.0%)	0 (0.0%)	11 (35.5%)	2 (6.5%)	13 (41.8%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
	CI users (n=31)	5 (16.1%)	0 (0.0%)	0 (0.0%)	11 (35.5%)	0 (0.0%)	14 (45.2%)	0 (0.0%)	1 (3.2%)	0 (0.0%)
	Total group (n=93)	11 (11.8%)	0 (0.0%)	2 (2.2%)	31 (33.33%)	2 (2.2%)	45 (48.4%)	0 (0.0%)	2 (2.2%)	0 (0.0%)
Favourable noise condition	NH (n=31)	1 (3.2%)	1 (3.2%)	1 (3.2%)	3 (9.7%)	5 (16.1%)	15 (48.4%)	1 (3.2%)	4 (12.9%)	0 (0.0%)
	HA users (n=31)	4 (12.9%)	3 (9.7%)	0 (0.0%)	7 (22.6%)	2 (6.5%)	11 (35.5%)	1 (3.2%)	3 (9.7%)	0 (0.0%)
	CI users (n=31)	11 (35.5%)	1 (3.2%)	1 (3.2%)	5 (16.1%)	2 (6.5%)	8 (25.8%)	1 (3.2%)	2 (6.5%)	0 (0.0%)
	Total group (n=93)	16 (17.2%)	5 (5.4%)	2 (2.2%)	15 (16.1%)	9 (9.7%)	34 (36.6%)	3 (3.2%)	9 (9.7%)	0 (0.0%)
Unfavourable noise condition	NH (n=31)	9 (29.0%)	0 (0.0%)	2 (6.5%)	12 (38.7%)	0 (0.0%)	8 (25.8%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
	HA users (n=31)	14 (45.2%)	0 (0.0%)	0 (0.0%)	9 (29.0%)	2 (6.5%)	5 (16.1%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
	CI users (n=31)	19 (61.3%)	0 (0.0%)	1 (3.2%)	4 (12.9%)	0 (0.0%)	6 (19.4%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
	Total group (n=93)	42 (46.2%)	0 (0.0%)	3 (3.3%)	25 (27.5%)	2 (2.2%)	19 (20.9%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

Note: DTE, Dual-task effect

FIGURES

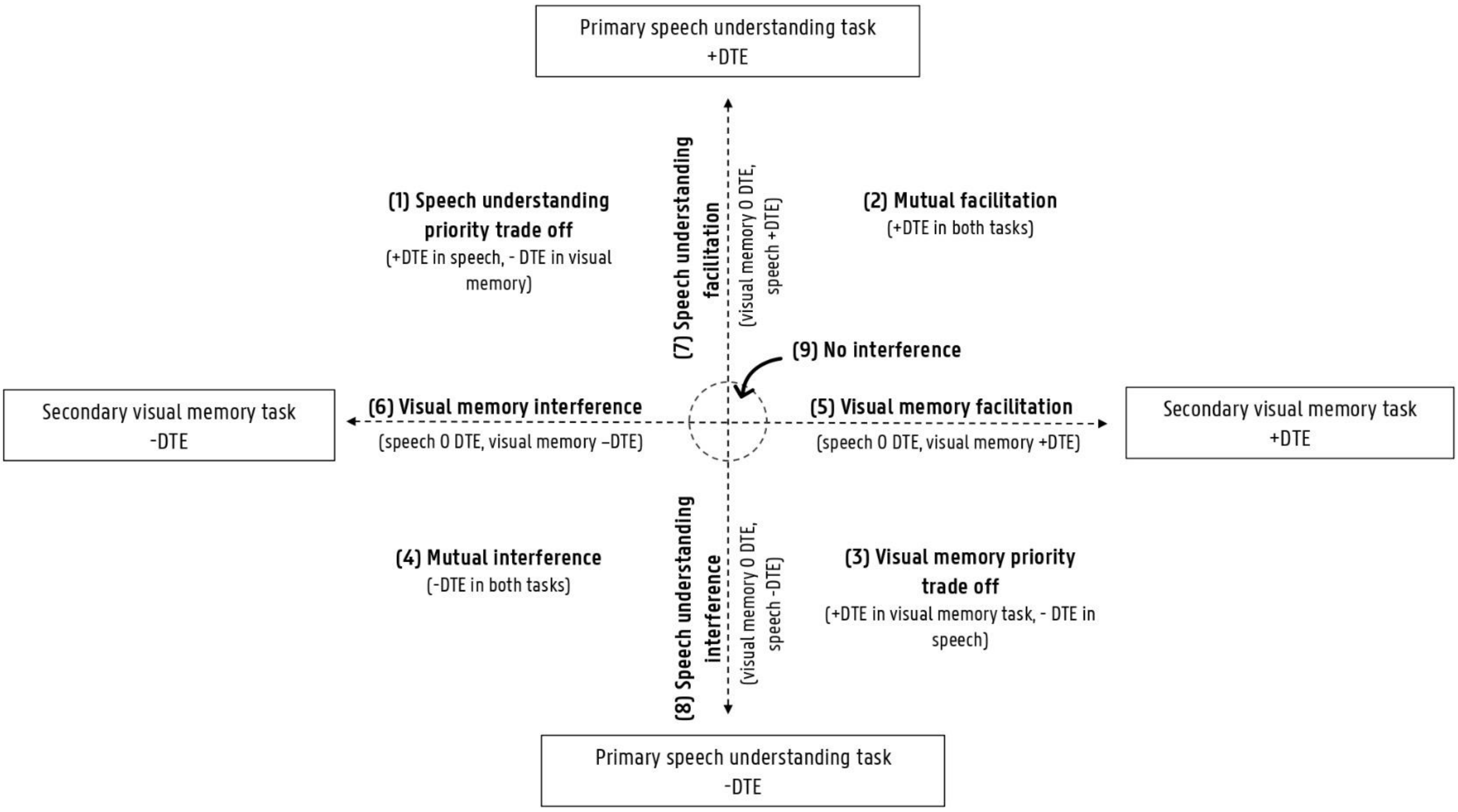

Figure 1: Illustration of conceptual framework for characterizing patterns of dual-task interference (adapted from Plummer et al. (2014))

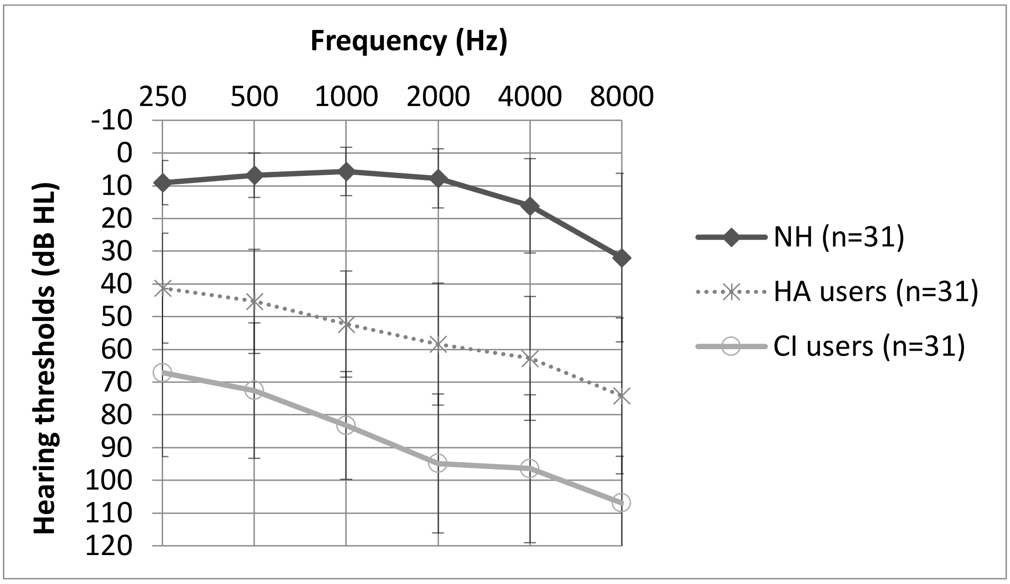

Figure 2: The mean and SD of the (unaided) hearing thresholds of the better ear per group

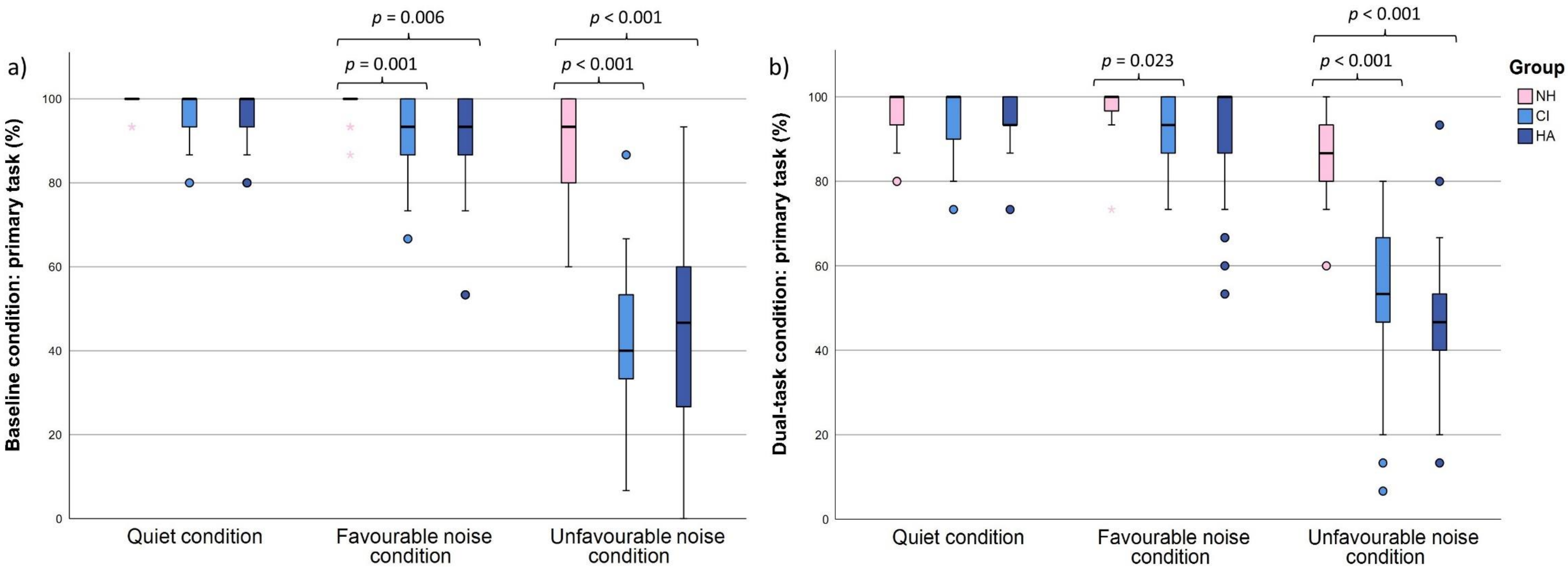

Figure 3: Results per group (NH, HA users, and CI users) for the primary task in the baseline condition (a) and dual-task condition (b)

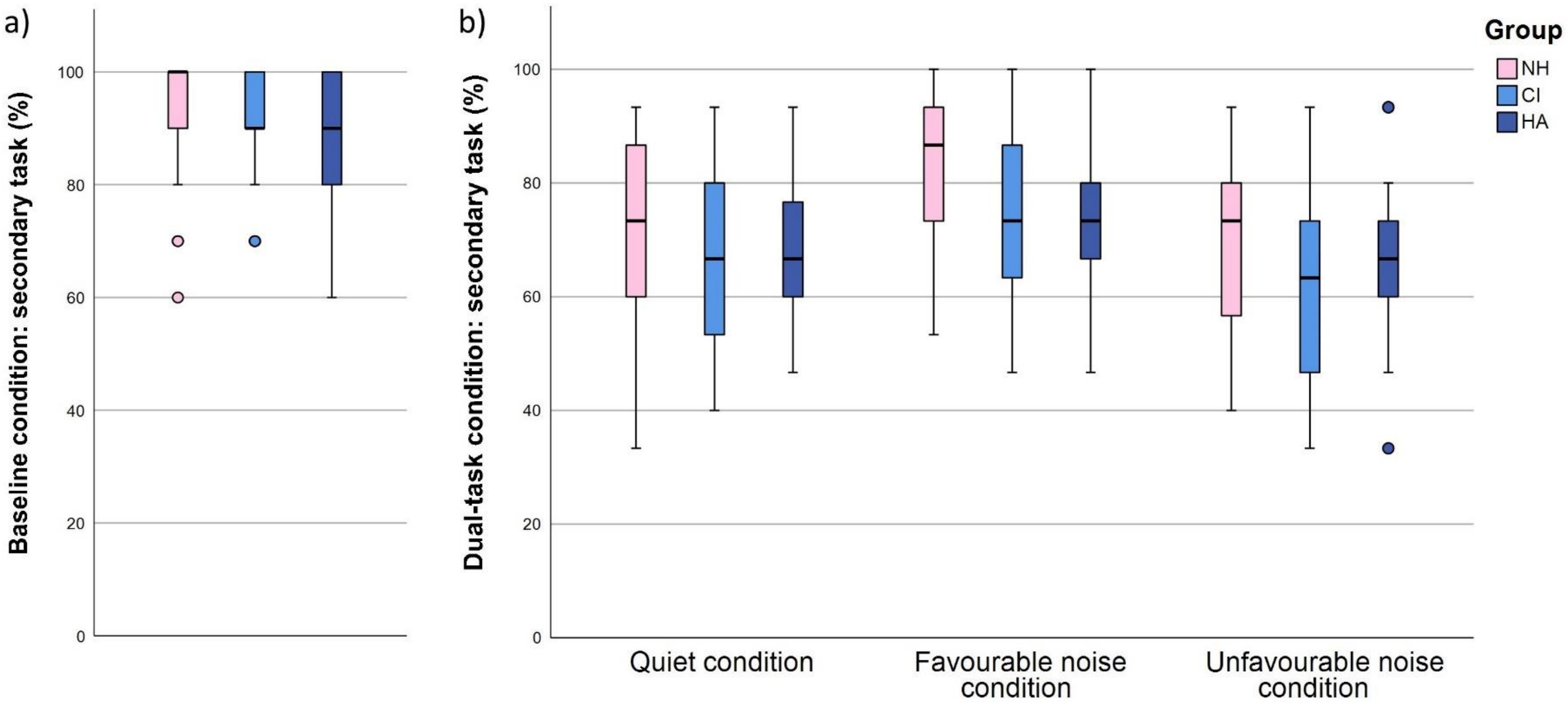

Figure 4: Results per group (NH, HA users, and CI users) for the secondary task in the baseline condition (a) and dual-task condition (b)

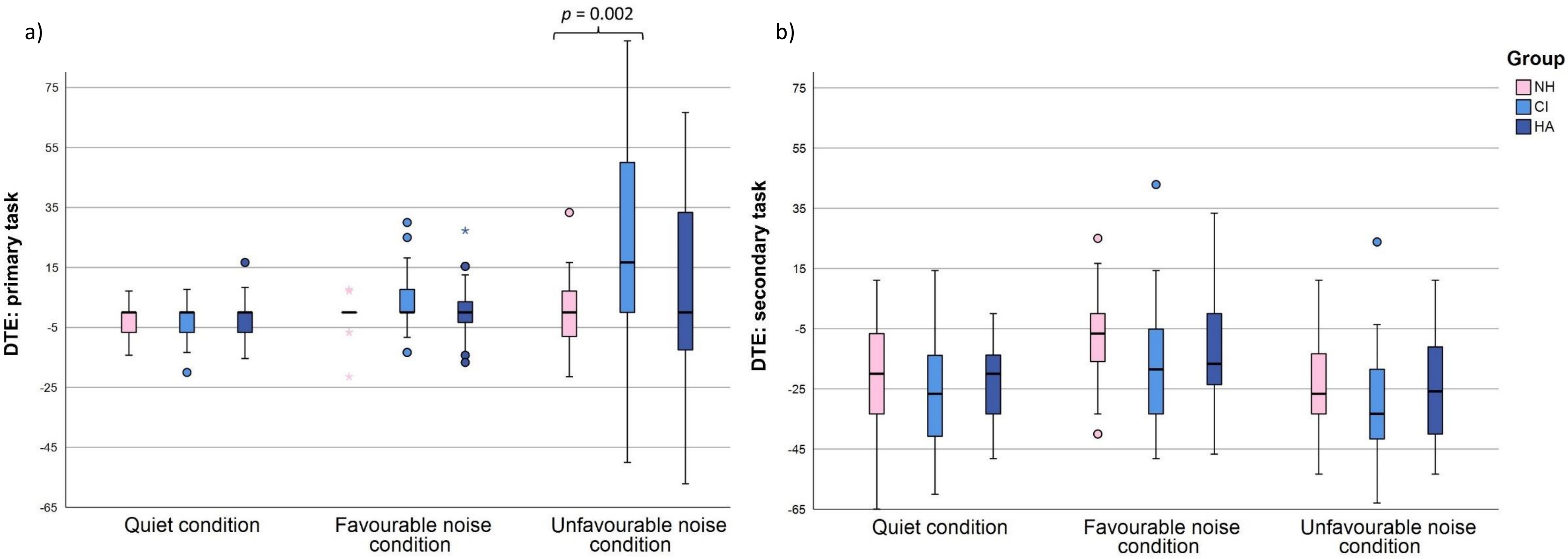

Figure 5: Results per group (NH, HA users, and CI users) for the dual-task effect values of the primary task (a) and the secondary task (b)

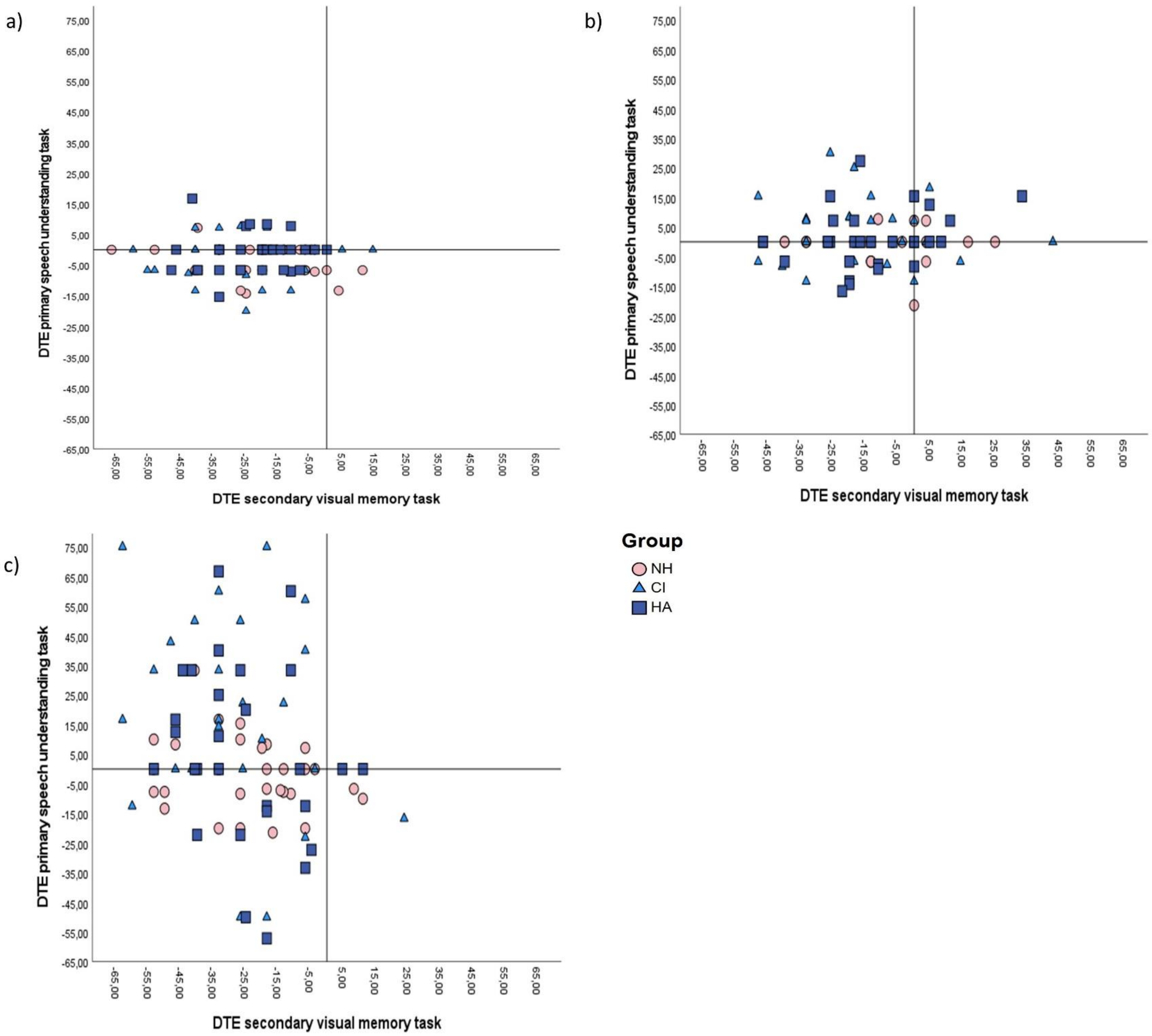

Figure 6: Framework of patterns of dual-task interference for the quiet condition (a), the favourable noise condition (b), and the unfavourable noise condition (c)

Note: It is possible for markers (i.e. circles, triangles, or squares) to overlap when multiple participants demonstrated the same outcome.

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SUPPLEMENTAL MATERIALS

Supplemental Material 1: Exact values of the descriptive data per group (NH, HA users, and CI users) and results for one-way ANOVA or Kruskall – Wallis for the primary task in the baseline- and dual-task condition

Variable	**NH**			**HA users**			**CI users**			**Results**	
	Mean (SD)	*Median*	*Range*	*Mean (SD)*	*Median*	*Range*	*Mean (SD)*	*Median*	*Range*	*Test Statistic*	*p*
Baseline condition											
Primary task - quiet listening condition (%)	99.14 (2.27)	100.00	93.33-100.00	95.70 (7.00)	100.00	80.00-100.00	96.56 (5.68)	100.00	80.00-100.00	χ2(2) = 5.01	0.082
Primary task - favourable noise condition (%)	98.49 (3.32)	100.00	86.67-100.00	90.54 (12.86)	93.33	53.33-100.00	90.75 (9.38)	93.33	66.67-100.00	χ2(2) = 15.53	< 0.001
Primary task - unfavourable noise condition (%)	88.17 (11.64)	93.33	60.00-100.00	44.30 (22.94)	46.67	0.00-93.33	43.44 (17.20)	40.00	6.67-86.67	F(2, 55.80) = 93.06	< 0.001
Dual-task condition											
Primary task - quiet condition (%)	96.13 (5.38)	100.00	80.00-100.00	94.41 (5.99)	93.33	73.33-100.00	94.19 (7.45)	100.00	73.33-100.00	χ2(2) = 1.75	0.416
Primary task - favourable noise condition (%)	97.63 (5.32)	100.00	73.33-100.00	90.97 (13.61)	100.00	53.33-100.00	93.12 (7.40)	93.33	73.33-100.00	χ2(2) = 7.92	0.019
Primary task - unfavourable noise condition (%)	86.02 (10.52)	86.67	60.00-100.00	46.44 (17.90)	46.67	13.33-93.33	53.11 (17.98)	53.33	6.67-80.00	F(2, 88) = 55.07	< 0.001

Note: in the favourable noise condition a SNR of +4 dB was applied, in the unfavourable noise condition an SNR of -6 dB was applied

Supplemental Material 2: Exact values of the descriptive data per group (NH, HA users, and CI users) and results for one-way ANOVA for the secondary task in the baseline- and dual-task condition

Variable	**NH**			**HA users**			**CI users**			**Results**	
	Mean (SD)	*Median*	*Range*	*Mean (SD)*	*Median*	*Range*	*Mean (SD)*	*Median*	*Range*	*Test Statistic*	*p*
Baseline condition											
Secondary visual memory task (%)	92.26 (11.17)	100.00	60.00-100.00	88.06 (13.27)	90.00	60.00-100.00	90.97 (9.44)	90.00	70.00-100.00	$\chi2(2) = 2.06$	0.357
Dual-task condition											
Secondary task - quiet condition (%)	73.12 (15.63)	73.33	33.33-93.33	67.31 (12.45)	66.67	46.67-93.33	66.67 (15.10)	66.67	40.00-93.33	$F(2, 90) = 1.87$	0.160
Secondary task - favourable noise condition (%)	83.01 (13.09)	86.67	53.33-100.00	74.84 (13.63)	73.33	46.67-100.00	75.05 (15.77)	73.33	46.67-100.00	$F(2, 90) = 3.33$	0.040
Secondary task - unfavourable noise condition (%)	68.82 (16.00)	73.33	40.00-93.33	65.78 (13.07)	66.67	33.33-93.33	63.56 (17.92)	63.33	33.33-93.33	$F(2, 88) = 0.86$	0.429

Note: in the favourable noise condition a SNR of +4 dB was applied, in the unfavourable noise condition an SNR of -6 dB was applied

Supplemental Material 3: Exact values of the descriptive data per group (NH, HA users, and CI users) and results for one-way ANOVA or Kruskall – Wallis for the dual-task effect (DTE = 100 × [score in dual-task condition - score in baseline condition]/score in baseline condition)

Variable	**NH**			**HA users**			**CI users**			**Results**	
	Mean (SD)	*Median*	*Range*	*Mean (SD)*	*Median*	*Range*	*Mean (SD)*	*Median*	*Range*	*Test Statistic*	*p*
DTE primary task - quiet condition	-3.04 (4.93)	0.00	-14.29-7.14	-1.09 (6.29)	0.00	-15.38-16.67	-2.36 (6.81)	0.00	-20.00-7.69	F(2, 90) = 0.83	0.441
DTE primary task - favourable noise condition	-0.84 (5.09)	0.00	-21.43-7.69	0.79 (9.49)	0.00	-16.67-27.27	3.30 (10.13)	0.00	-13.33-30.00	χ2(2) = 2.87	0.238
DTE primary task - unfavourable noise condition	-1.57 (12.09)	0.00	-21.43-33.33	19.46 (63.23)	0.00	-57.14-250.00	22.59 (37.79)	16.67	-50.00-100.00	χ2(2) = 9.61	0.008
DTE secondary task - Quiet condition	-19.91 (17.54)	-20.00	-66.67-11.11	-22.86 (12.55)	-20.00	-48.15-0.00	-26.19 (17.46)	-26.67	-60.00-14.29	F(2, 90) = 1.19	0.308
DTE secondary task - favourable noise condition	-9.13 (15.43)	-6.67	-40.00-25.00	-13.74 (17.03)	-16.67	-46.67-33.33	-16.74 (19.64)	-18.52	-48.15-42.86	F(2, 90) = 1.50	0.229
DTE secondary task - unfavourable noise condition	-24.82 (17.71)	-26.67	-53.33-11.11	-24.38 (16.58)	-25.83	-53.33-11.11	-30.47 (19.40)	-33.33	-62.96-23.81	F(2, 88) = 1.08	0.343

Note: in the favourable noise condition a SNR of +4 dB was applied, in the unfavourable noise condition an SNR of -6 dB was applied