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Effects of the Contralateral Routing of Signal (CROS) system on listening effort, participation restriction, and quality of life in unilateral hearing loss

Efeitos do Sistema de Roteamento Contralateral de Sinal (CROS) no esforço de escuta, restrição de participação e qualidade de vida na perda auditiva unilateral

Efectos del Sistema de Enrutamiento Contralateral de la Señal (CROS) sobre el esfuerzo de escucha, la restricción de participación y la calidad de vida en la pérdida auditiva unilateral

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Abstract

Objective: To analyze listening effort, participation restriction, and quality of life in adults with severe-to-profound unilateral sensorineural hearing loss before and after adaptation to the Contralateral Routing of Signal (CROS) system, and to investigate the influence of age on dual-task performance. **Methods:** This longitudinal pre–post intervention study initially identified 49 eligible clinical records.

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Authors' Contributions:
ACBG, RJSF, MFCGM: reviewed data from all sites and provided interpretive analysis, wrote and reviewed the main paper. All authors discussed the results and implications, commented on the manuscript at all stages and approved the final version to be published.

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Twenty-five patients were scheduled for participation and, after losses and exclusions during follow-up, 19 completed both assessment stages and comprised the analytical sample. Participants were assessed before CROS adaptation and eight months later. Participation restriction was evaluated using the Hearing Handicap Inventory for Adults (HHIA), quality of life using the WHOQOL-BREF, and listening effort using a dual-task paradigm combining speech perception in noise with a visual color-memory task (PALETA). **Results:** CROS use significantly reduced HHIA scores and listening effort measured by the number of correct responses in the secondary task. Overall quality of life and general health satisfaction did not change significantly, whereas the physical, psychological, social relationships, and environment domains improved. Speech perception in noise did not differ significantly between single- and dual-task conditions. Age influenced the number of correct responses in the secondary task but not response time. **Conclusion:** CROS adaptation was associated with reduced participation restriction and listening effort and with improvement in specific WHOQOL-BREF domains; however, no significant change was observed in overall quality of life or general health satisfaction.

Keywords: Unilateral Hearing Loss; Listening Effort; Multitasking Behavior; Quality of Life.

Resumo

Objetivo: Analisar o esforço de escuta, a restrição de participação e a qualidade de vida de adultos com perda auditiva sensorioneural unilateral de grau severo a profundo antes e após a adaptação ao sistema de Roteamento Contralateral de Sinal (CROS), além de investigar a influência da idade no desempenho em dupla tarefa. **Métodos:** Estudo longitudinal de intervenção pré–pós que identificou inicialmente 49 prontuários elegíveis. Vinte e cinco pacientes foram agendados e, após perdas e exclusões durante o seguimento, 19 completaram as duas etapas de avaliação e constituíram a amostra analítica. Os participantes foram avaliados antes da adaptação ao CROS e oito meses depois. A restrição de participação foi avaliada pelo Hearing Handicap Inventory for Adults (HHIA), a qualidade de vida pelo WHOQOL-BREF e o esforço de escuta por paradigma de dupla tarefa, combinando percepção de fala no ruído e tarefa visual de memória de cores (PALETA). **Resultados:** O uso do CROS reduziu significativamente os escores do HHIA e o esforço de escuta mensurado pelo número de respostas corretas na tarefa secundária. Não houve mudança significativa na qualidade de vida geral nem na satisfação geral com a saúde, enquanto os domínios físico, psicológico, relações sociais e meio ambiente melhoraram. A percepção de fala no ruído não diferiu significativamente entre as condições de tarefa única e dupla. A idade influenciou o número de respostas corretas na tarefa secundária, mas não o tempo de resposta. **Conclusão:** A adaptação ao CROS esteve associada à redução da restrição de participação e do esforço de escuta e à melhora de domínios específicos do WHOQOL-BREF; entretanto, não houve mudança significativa na qualidade de vida geral ou na satisfação geral com a saúde.

Palavras-chave: Perda Auditiva Unilateral; Esforço de Escuta; Comportamento Multitarefa; Qualidade de Vida.

Resumen

Objetivo: Analizar el esfuerzo de escucha, la restricción de participación y la calidad de vida de adultos con pérdida auditiva sensorioneural unilateral de grado severo a profundo antes y después de la adaptación al sistema de Enrutamiento Contralateral de la Señal (CROS), además de investigar la influencia de la edad en el desempeño en doble tarea. **Métodos:** Estudio longitudinal de intervención pre–post que identificó inicialmente 49 historias clínicas elegibles. Veinticinco pacientes fueron programados para participar y, tras pérdidas y exclusiones durante el seguimiento, 19 completaron ambas etapas de evaluación y constituyeron la muestra analítica. Los participantes fueron evaluados antes de la adaptación al CROS y ocho meses después. La restricción de participación se evaluó mediante el Hearing Handicap Inventory for Adults (HHIA), la calidad de vida mediante WHOQOL-BREF y el esfuerzo de escucha mediante un paradigma de doble tarea que combinó percepción del habla en ruido y una tarea visual de memoria de colores (PALETA). **Resultados:** El uso de CROS redujo significativamente las puntuaciones del HHIA y el esfuerzo de escucha medido por el número de respuestas correctas en la tarea secundaria. No hubo

cambios significativos en la calidad de vida general ni en la satisfacción general con la salud, mientras que mejoraron los dominios físico, psicológico, relaciones sociales y medio ambiente. La percepción del habla en ruido no difirió significativamente entre las condiciones de tarea única y doble. La edad influyó en el número de respuestas correctas en la tarea secundaria, pero no en el tiempo de respuesta. **Conclusión:** La adaptación al CROS se asoció con una reducción de la restricción de participación y del esfuerzo de escucha y con una mejoría en dominios específicos del WHOQOL-BREF; sin embargo, no se observaron cambios significativos en la calidad de vida general ni en la satisfacción general con la salud.

Palabras clave: Pérdida Auditiva Unilateral; Esfuerzo de Escucha; Conducta Multitarea; Calidad de Vida.

Introduction

A Unilateral Hearing Loss (UNIHL) is characterized by hearing loss in one ear, while hearing in the other ear remains within normal limits. In Brazil [1], over 2.3 million people have some form of hearing impairment, representing 1.1% of the population. In the United States[2], the overall prevalence of UNIHL in adults is 7.2%, with only 2.0% of these individuals using hearing aids. UNIHL can result from various etiologies, including congenital, infectious, traumatic, and ototoxic causes[3].

The impacts of UNIHL are extensive, affecting not only auditory perception but also the social, emotional, and functional well-being of individuals. People with UNIHL often experience difficulties in environments with background noise, compromising their ability to understand speech and localize sounds[4]. This deficit is particularly pronounced in complex environments, where the lack of binaural auditory cues hinders the distinction of sound sources[4,5]. Moreover, individuals with UNIHL may face significant challenges in socialization, academic and work performance, and overall quality of life. The additional effort required to hear in noisy environments can lead to auditory fatigue and increased stress, negatively impacting general well-being[6].

The difficulties resulting from UNIHL also manifest in interaural differences that affect spatial perception and auditory comprehension [6]. Individuals with this condition frequently report tinnitus and a reduced sensation of sound intensity in the affected ear. Changes in auditory abilities and sensory experiences can result in significant emotional and social impacts, such as isolation, frustration, and anxiety[4,6,7]. Given the challenge of understanding speech in difficult environments, these individuals may experience an increase in listening effort, that is, the amount of cognitive and attentional resources needed to process auditory information[7].

To mitigate the adverse effects of UNIHL, various rehabilitation solutions have been developed, including the use of Contralateral Routing of Signal (CROS). The CROS system is a technology present in Electronic Sound Amplification Device (EASD) that transfers sound captured by the poorer ear to the better ear via a microphone and transmitter. This allows users to receive auditory information from the affected side, improving spatial sound perception and speech comprehension[3]. Additionally, the CROS system may be indicated for individuals with Unilateral Hearing Loss, with the aim of improving communication and reducing listening effort[5].

Non-auditory aspects, such as participation restriction and quality of life in individuals using the CROS system, remain underexplored, particularly in relation to listening effort. In this context, the present study aimed to analyze listening effort in individuals with severe-to-profound unilateral sensorineural hearing loss before and after CROS adaptation; to evaluate participation restriction and quality of life before and after adaptation; and to investigate the influence of age on dual-task performance.

Methods

This is a longitudinal pre–post intervention study approved by the Research Ethics Committee of the Faculdade de Odontologia de Bauru of Universidade de São Paulo- FOB/USP, under CAAE no. 86783318.9.0000.5417. Data collection was conducted in two stages at the Audiology Clinic of FOB/USP: the first from July to August 2018 and the second from February to April 2019, approximately eight months after CROS adaptation. Inclusion criteria were enrollment at the clinic,

severe-to-profound unilateral sensorineural hearing loss, and age between 18 and 64 years.

49 clinical records met the initial eligibility criteria. Four patients were excluded because of repeated unexcused absences, five could not be contacted by telephone, one had died, one had discontinued clinical follow-up, and 13 were unavailable on the proposed assessment dates. Thus, 25 patients were scheduled. Of these, two were excluded after missing two appointments, one declined CROS because of the need to use two devices, one had a hearing aid functioning adequately and therefore did not require replacement, and two did not return for the second assessment. The final analytical sample comprised 19 participants who completed both stages.

The wireless CROS system consisted of a transmitter fitted to the ear with hearing loss and a receiver fitted to the normal-hearing ear. Mini behind-the-ear receiver-in-canal devices were used. An open dome was used on the normal-hearing side. Participants were instructed to use the devices for at least eight hours per day and received guidance regarding handling and cleaning. At the second assessment, device functioning and daily use were checked using the device software; use below the recommended minimum was an exclusion criterion.

CROS fitting was verified using real-ear unaided response (REUR) and real-ear aided response (REAR) measurements with an Aurical FreeFit system (GN Otometrics) in an acoustically treated room. The probe tube remained in the normal-hearing ear, and measurements were obtained with the loudspeaker positioned according to the CROS verification procedure. The chair was positioned 50 cm from the loudspeaker, and the geometric method was used to place the probe tube approximately 4 mm from the tip of the dome. Speech noise was presented at a constant level of 65 dB SPL.

Participation restriction was assessed using the Hearing Handicap Inventory for Adults (HHIA), administered as an interview. The examiner read the 25 questions with the participant, who selected "yes" (4 points), "sometimes" (2 points), or "no" (0 points). Total scores range from 0 to 100, with higher scores indicating greater perceived participation restriction; scores of 0–16 indicate no perceived restriction, 18–30 mild, 32–42 moderate, and >42 severe restriction. Quality of life was assessed using the World Health Organization Quality of Life-BREF (WHOQOL-BREF), which contains 26 items: two general items addressing overall quality of life and general health perception and 24 items distributed across physical, psychological, social relationships, and environment domains. Responses use a five-point Likert scale, with higher scores indicating better quality of life.

Listening effort was assessed using a dual-task paradigm. The primary task was speech perception in noise using the Portuguese Sentence Lists (LSP). Two lists from 1B to 6B were randomly selected at the first assessment, totaling 20 sentences; different lists were used at follow-up to reduce memorization effects. Testing was performed in an acoustically treated booth in free field, with the loudspeaker at 0° azimuth. Sentences were presented at 65 dB and noise at 60 dB, corresponding to a +5 dB signal-to-noise ratio. The better ear was not occluded because testing was performed in free field and the CROS system routes the signal to this ear.

The secondary task was the PALETA visual memory task. Participants memorized and reproduced 20 randomly generated four-color sequences on a tablet. A response was considered correct only when the four colors were reproduced in the same order presented by the software. Each stimulus and interstimulus interval lasted 0.4 seconds. The platform recorded total response time and total number of correct responses. Before data collection, participants were trained on the primary task, secondary task, and dual task. During the dual task, both tasks were performed simultaneously, and participants were instructed to prioritize the speech-perception task.

All inferential pre–post analyses were based on the 19 participants who completed both assessment stages. Data was analyzed using IBM SPSS Statistics, version 24. A significance level of 5% ($\alpha = 0.05$) was adopted for all analyses. Comparisons between pre- and post-CROS conditions were performed using paired statistical tests according to the distribution and characteristics of each variable. The paired t-test was used for variables analyzed parametrically, whereas the Wilcoxon signed-rank test was applied to non-parametric paired data. For comparisons of the number of correct responses across the single-task, dual-task, and dual-task with CROS conditions, a one-way repeated-measures analysis of variance (ANOVA) was performed, followed by Tukey's post hoc test for multiple comparisons. Response times across the three task

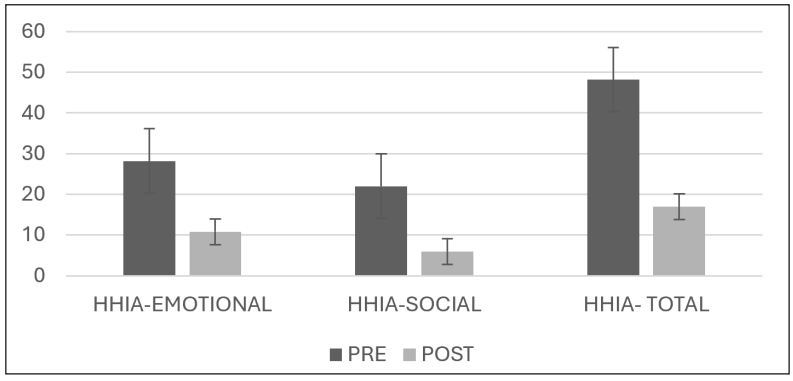
conditions were compared using the Friedman test, followed by multiple comparisons. The influence of age on performance in the secondary task, considering both the number of correct responses and response time, was examined by covariance analysis. When applicable, results were expressed as means and 95% confidence intervals for parametric variables and medians for non-parametric variables.

Results

19 participants with severe-to-profound unilateral sensorineural hearing loss complete pre- and post-adaptation data were included in the analyses. Participants ranged in age from 33 to 64 years (mean = 48.84 years; SD = 7.92). 12 participants (63.2%) were male and seven (36.8%) were female. Regarding the degree of hearing loss, 16 participants (84.2%) had profound hearing loss and three (15.8%) had severe hearing loss. The affected ear was the left ear in 11 participants (57.9%) and the right ear in eight (42.1%).

Regarding participation restriction, the emotional subscale of the HHIA (HHIA-EMOTIONAL) showed a significant reduction after CROS adaptation. The mean score decreased from 28.211 before adaptation to 10.842 after adaptation (paired t-test: $t(18) = 8.326$, $p < 0.001$), corresponding to a mean reduction of 17.369 points. The 95% confidence interval (CI) for the mean pre–post difference ranged from 12.986 to 21.751 (Figure 1).

A significant reduction was also observed in the social subscale of the HHIA (HHIA-SOCIAL). The median score decreased from 22 before adaptation to 6 after adaptation, corresponding to a 16-point reduction (Wilcoxon signed-rank test: $W = -190.000$, $p < 0.001$) (Figure 1).



Legend: PRE = pre-CROS system adaptation; POST = post-CROS system adaptation.
Source: Study Data.

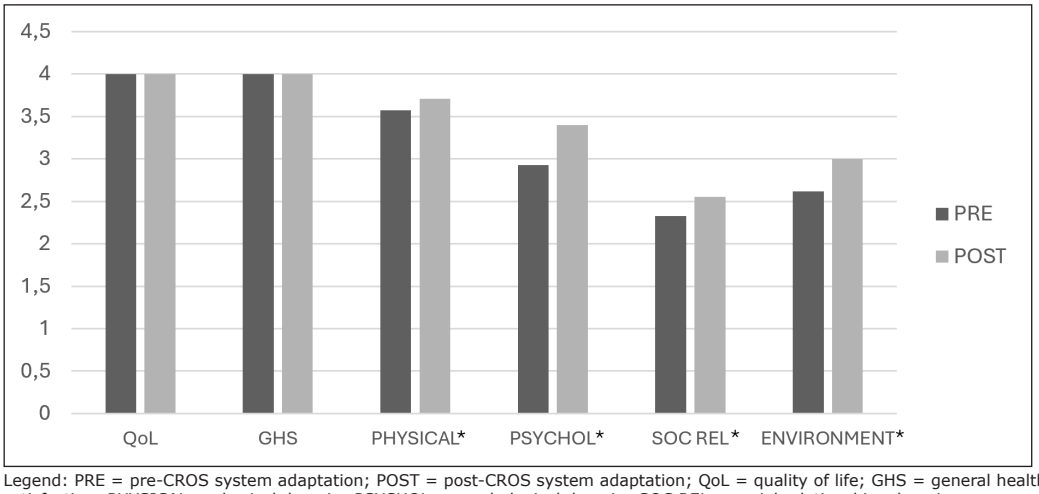
Figure 1. Means and minimum and maximum values of HHIA aspects, pre- and post-CROS system adaptation

The total HHIA score also decreased significantly after CROS adaptation (paired t-test: $t(18) = 9.338$, $p < 0.001$). The mean total score decreased from 48.211 before adaptation to 16.947 after adaptation, corresponding to a mean reduction of 31.264 points. The 95% CI for the mean pre–post difference ranged from 24.229 to 38.297. According to the HHIA classification criteria, the mean pre-adaptation score was within the severe participation-restriction range (>42), whereas the mean post-adaptation score was within the range indicating no perceived participation restriction (0–16).

Participant performance across the WHOQOL-BREF domains before and after CROS adaptation is presented in Figure 2. No statistically significant differences were observed for the two general WHOQOL-BREF items. The median score for overall QoL remained 4 before and after CROS adaptation (Wilcoxon signed-rank test: $W = 15.000$, $p = 0.063$), and the median score for General Health Satisfaction (GHS) also remained 4 in both assessments ($W = 10.000$, $p = 0.125$). Thus, no statistically significant changes were observed in overall quality of life or general health satisfaction after CROS adaptation.

In contrast, statistically significant differences were observed in the Physical, Psychological, Social Relationships, and Environment domains. In the Physical domain, the median score increased from 3.57 before adaptation to 3.71 after adaptation (Wilcoxon signed-rank test: $W = 28.000$, $p = 0.016$). In the Psychological domain, the mean score increased from 2.936 before adaptation to 3.401 after adaptation (paired t-test: $t(18) = 9.338$, $p < 0.001$), corresponding to a mean increase of 0.465 points. The 95% CI for the pre–post difference ranged from 0.305 to 0.625.

In the Social Relationships domain, the median score increased from 2.33 before adaptation to 2.66 after adaptation (Wilcoxon signed-rank test: $W = 78.000$, $p = 0.001$). Similarly, in the Environment domain, the median score increased from 2.62 to 3.00 ($W = 28.000$, $p = 0.016$). Therefore, although no significant changes were observed in overall quality of life or general health satisfaction, significant increases were observed in scores for the four specific WHOQOL-BREF domains evaluated (Figure 2).



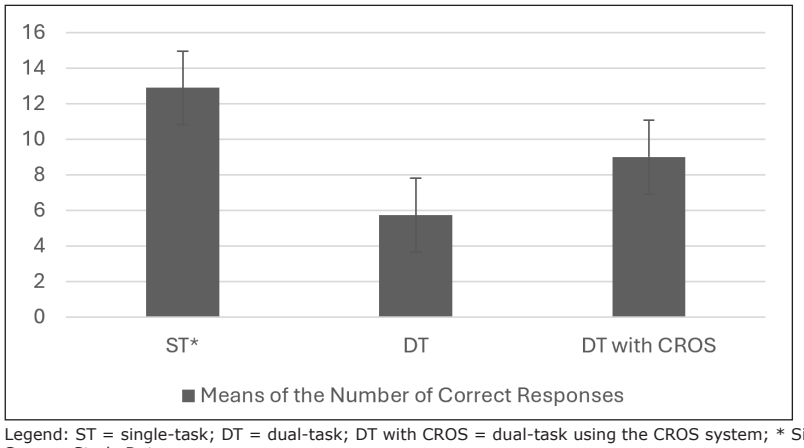
Legend: PRE = pre-CROS system adaptation; POST = post-CROS system adaptation; QoL = quality of life; GHS = general health satisfaction; PHYSICAL = physical domain; PSYCHOL = psychological domain; SOC REL = social relationships domain; ENVIRONMENT = environment domain; *Statistically significant pre–post difference ($p < 0.05$).
Source: Study Data.

Figure 2. Comparison of responses across all domains of the WHOQOL questionnaire, pre- and post-CROS system adaptation

Speech perception in noise, assessed as the primary task using the Portuguese Sentence List, was compared between the single-task and dual-task conditions. Before CROS adaptation, no statistically significant difference was observed between the single-task and dual-task conditions (Wilcoxon signed-rank test: $W = -6.000$, $p = 0.250$), with a median of 20 correct responses in both conditions. Similarly, after CROS adaptation, speech perception in noise did not differ significantly between the single-task and dual-task conditions, with a median of 20 correct responses in both conditions ($W = 0.000$, $p = 1.000$). Thus, performance on the primary speech-perception task was maintained when the secondary task was performed simultaneously, both before and after CROS adaptation.

Listening effort was assessed through performance on the secondary PALETA task, considering both the number of correct responses (NCR) and response time (RT). Three conditions were analyzed: single-task (ST), dual-task without CROS (DT), and dual-task with CROS (DT_CROS). The single-task condition was assessed only before CROS adaptation because it represented baseline performance on the secondary visual-memory task in the absence of the concurrent speech-perception task.

For the number of correct responses, participants achieved a mean of 12.895 correct responses in the single-task condition, 5.737 in the dual-task condition without CROS, and approximately 9 correct responses in the dual-task condition with CROS. A one-way repeated-measures analysis of variance showed a significant effect of task condition on the number of correct responses ($F = 79.855$, $p < 0.001$) (Figure 3). Post hoc comparisons showed significant differences among all three conditions ($p < 0.001$), with the highest number of correct responses observed in the single-task condition, followed by the dual-task condition with CROS and the dual-task condition without CROS (Table 1).



Legend: ST = single-task; DT = dual-task; DT with CROS = dual-task using the CROS system; * Significant difference.
Source: Study Data.

Figure 3. Mean number of correct responses in the PALETA secondary task across single-task, dual-task, and dual-task with CROS conditions

For the number of correct responses, listening effort was calculated from the change in secondary-task performance between the single-task and dual-task conditions, as follows:

- Pre-CROS: NCR_DT − NCR_ST
- Post-CROS: NCR_DT_CROS − NCR_ST

Comparison of the listening-effort measures derived from the pre- and post-CROS conditions showed a significant difference (paired t-test: $t(18) = -6.044$, $p < 0.001$), indicating better secondary-task performance during dual-task execution when participants used the CROS system.

Pairwise comparisons of the number of correct responses across task conditions are presented in Table 1. The mean differences were 7.1 between ST and DT, 3.9 between ST and DT_CROS, and 3.3 between DT_CROS and DT, with all comparisons reaching statistical significance ($p < 0.001$).

Table 1. Pairwise comparisons of the number of correct responses in the PALETA task

Tasks	Difference between means	p-value
NCR- ST versus NCR- DT	7.1	<0.001*
NCR-ST versus NCR-DT(CROS)	3.9	<0.001*
NCR-DT(CROS) versus NCR-DT	3.3	<0.001*

Legend: NCR = number of correct responses; ST = single-task; DT = dual-task; DT (CROS) = dual-task using the CROS system; * Significant difference.
Source: Study Data.

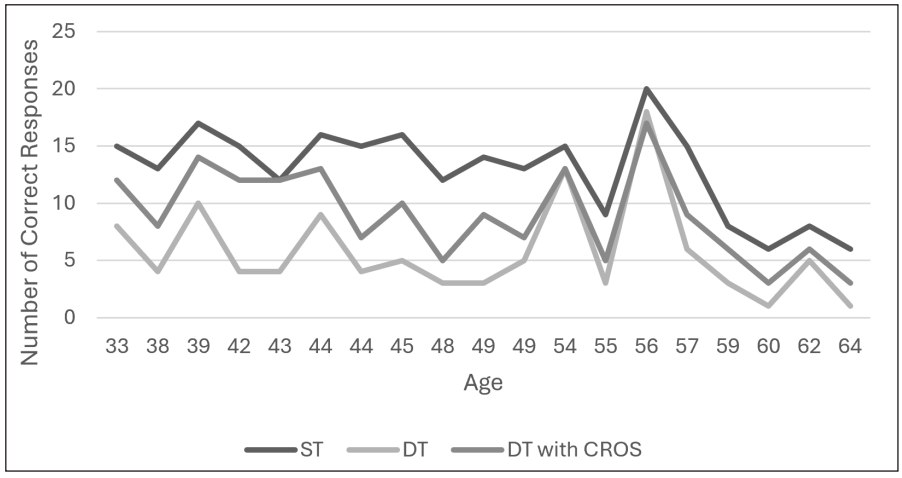
Response time in the PALETA task was also analyzed across the single-task (RT_ST), dual-task (RT_DT), and dual-task with CROS (RT_DT_CROS) conditions. Median response times were 3.2 seconds in the single-task condition, 3.6 seconds in the dual-task condition, and 3.5 seconds in the dual-task condition with CROS. The Friedman test identified a significant overall difference in response time across the three conditions ($\chi^2(2) = 16.441$, $p < 0.001$). Subsequent pairwise comparisons showed a significant difference between RT_DT and RT_ST, whereas the differences between RT_DT and RT_DT_CROS and between RT_DT_CROS and RT_ST were not statistically significant. Thus, although response time increased when the secondary task was performed concurrently with the primary task, no significant difference in response time was demonstrated between the dual-task conditions with and without CROS.

Listening effort based on response time was also calculated from the change in secondary-task performance between the single-task and dual-task conditions, as follows:

- Pre-CROS: RT_DT − RT_ST
- Post-CROS: RT_DT_CROS − RT_ST

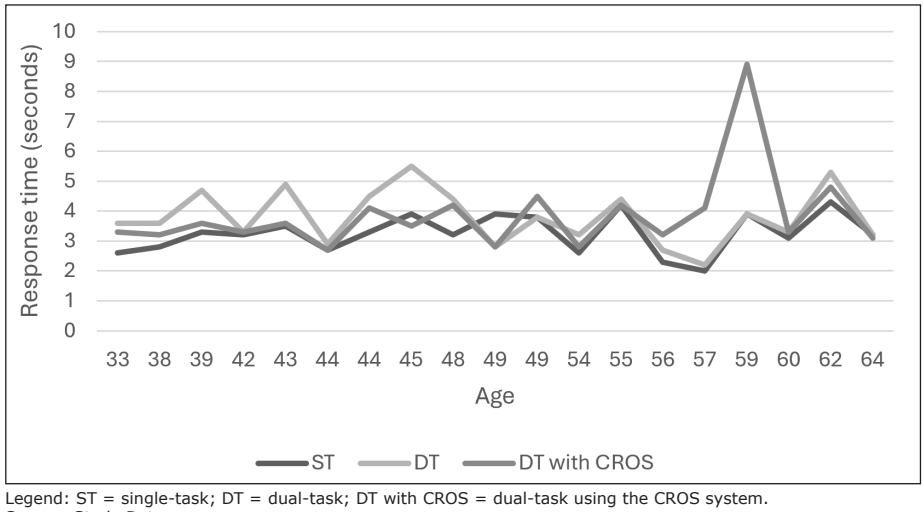
Comparison of the response-time-based listening-effort measures showed no statistically significant difference between the pre- and post-CROS conditions (Wilcoxon signed-rank test: $W = 83.5$, $p = 0.438$). Thus, while a significant pre–post difference in listening effort was observed when considering the number of correct responses, no significant difference was observed when response time was used as the outcome measure.

The influence of age on secondary-task performance was also examined. Covariance analysis indicated that age influenced the number of correct responses in the PALETA task, with the number of correct responses decreasing with increasing age (Figure 4). In contrast, covariance analysis indicated no influence of age on PALETA response time (Figure 5). Thus, within the age range represented in the study sample, age was associated with accuracy in the secondary task but not with the time required to respond.



Legend: ST = single-task; DT = dual-task; DT with CROS = dual-task using the CROS system.
Source: Study Data.

Figure 4. Number of correct responses in the PALETA task according to participants' age across task conditions



Legend: ST = single-task; DT = dual-task; DT with CROS = dual-task using the CROS system.
Source: Study Data.

Figure 5. PALETA response time according to participants' age across task conditions.

Discussion

Understanding the perception of individuals with UNIHL regarding their hearing loss and primary complaints is an essential tool for the speech-language pathologist during the process of counseling and selecting hearing devices. This understanding also allows for aligning expectations concerning the use of amplification. The American Academy of Audiology Clinical Practice Guidelines for adults with severe to profound unilateral hearing loss[8] emphasize that this initial validation can directly influence the expected outcomes for individuals, both positive and negative.

The perception of participation restriction, as assessed through the HHIA, indicated a significant improvement in responses related to emotional and social aspects after adaptation to the CROS system.

This was also observed when considering the total questionnaire score. The mean total HHIA score decreased from a value within the severe participation-restriction range before CROS adaptation to a markedly lower value after adaptation, approaching the cutoff for absence of perceived participation restriction. These findings corroborate the results of studies[9,10] that emphasize the importance of identifying some degree of participation restriction to guide interventions and raise patient awareness.

The reduction in participation restriction with the use of hearing devices is well documented[11]. In the present study, the significant reductions in the emotional, social, and total HHIA scores indicate lower perceived participation restriction following CROS adaptation. Rather than demonstrating complete elimination of participation restriction in all participants, these findings support a substantial reduction in its perceived impact. Similar benefits in auditory, social, and emotional aspects have been reported in other research[11-13].

Quality of life was investigated to assess the impact of UNIHL beyond auditory aspects. The present findings showed no statistically significant change in overall quality of life or general health satisfaction after CROS adaptation. However, significant increases were observed in the Physical, Psychological, Social Relationships, and Environment domains of the WHOQOL-BREF. Thus, the results suggest changes in specific dimensions of quality of life rather than an overall improvement in quality of life. Sano et al.[14] did not find significant differences between individuals with unilateral hearing loss and bilateral hearing loss but reported more pronounced impacts on quality of life compared to normal hearers. These differences can affect performance at work, social activities, and mental health[15,16].

Although WHOQOL is recommended for assessing non-auditory issues[8], it has been little used in studies with CROS system users. Other studies in the literature[17,18] have also found improvements in quality of life among users of bone-anchored transcutaneous devices and the CROS system. These findings provide context for the significant changes observed in specific WHOQOL-BREF domains in the present study, while the absence of significant changes in overall quality of life and general health satisfaction should also be considered.

The word "effort" in the auditory context refers to the challenges faced by individuals with UNIHL, even when using hearing aids, especially those who believe that hearing with one ear is sufficient. The literature on auditory effort has focused more on individuals with bilateral hearing loss, cochlear implant adaptations, and conventional hearing aids, leaving a gap concerning unilateral impairment. In this scenario, the present study, along with that of Choi et al.[19], contributes to the still limited evidence regarding listening effort associated with the use of the CROS system.

The dual-task paradigm, used to measure auditory effort, can be influenced by the complexity of the tasks involved. The lack of standardization in the secondary task results in variations in outcomes across studies[20]. In this study, the PALETA platform was used as the secondary task to quantify performance through both the number of correct responses and response time. Speech-perception performance in noise remained unchanged between the single-task and dual-task conditions, both before and after CROS adaptation. However, this maintenance of primary-task performance should not be interpreted as evidence that the dual-task condition required no additional cognitive resources. Participants were instructed to prioritize the primary task, and the reduction in the number of correct responses in the secondary task from the single-task to the dual-task condition suggests that maintaining speech-perception performance occurred alongside reduced secondary-task accuracy.

The results obtained from the two secondary-task measures should be interpreted separately. For the number of correct responses, performance decreased from the single-task to the dual-task condition and subsequently increased when the dual task was performed with the CROS system. Accordingly, the comparison of the listening-effort measures based on the number of correct responses showed a significant difference between the pre- and post-CROS conditions. In contrast, although response time differed significantly across the three task conditions overall, there was no significant difference between the dual-task conditions with and without CROS. Moreover, the listening-effort measure derived from response time did not differ significantly between the pre- and post-CROS conditions. Therefore, the evidence for reduced listening effort with CROS was observed in secondary-task accuracy, but not in response time.

This distinction is relevant because the CROS system did not significantly improve speech-

perception performance in noise in the primary task. Instead, its effect was observed in the participants' ability to maintain greater accuracy in the concurrent secondary task while primary-task performance remained stable. This finding may be relevant for daily activities that require divided attention, such as listening and taking notes simultaneously[21]. Previous studies[22-24] also suggest that bilateral auditory interventions are more effective in reducing auditory effort.

Despite this, the influence of age on the number of correct responses was significant, with younger individuals performing better on the PALETA task. Age, however, did not influence response time, indicating that its association with secondary-task performance was observed for accuracy rather than response speed. This result is consistent with the literature, which associates age with increased auditory effort due to changes in cognitive processes[25-27] . Choi et al.[19] reinforce these findings by highlighting that the positive and negative effects of CROS on localization and speech perception were significantly correlated with personal factors such as age, hearing threshold in the better ear, and unaided psychoacoustic performance.

In the present study, auditory effort was measured by performance on the secondary task, considering both the number of correct responses and response time, as suggested by Picou, Ricketts, and Hornsby[28]. The number of correct responses was the measure that demonstrated a significant difference between the pre- and post-CROS listening-effort conditions, whereas response time did not. Taken together, these findings suggest that CROS use may reduce listening effort as reflected by secondary-task accuracy in individuals with UNIHL, although this effect was not consistently demonstrated across both measures of the dual-task paradigm. Therefore, the findings support a potential role of the CROS system in reducing listening effort while also highlighting the importance of considering the specific outcome used to quantify this construct.

This study has some limitations that should be considered when interpreting the findings. The relatively small sample size and the absence of a control group limit the generalizability of the results and preclude establishing a causal relationship between CROS use and the observed changes. Although device data logging was used to verify adherence to the recommended minimum use of eight hours per day, the association between daily duration of CROS use and the study outcomes was not examined. Finally, the wide age range of the sample should be considered, particularly because age was associated with the number of correct responses in the secondary task. Future studies with larger samples and controlled designs may help clarify these findings and further investigate factors associated with individual variability in CROS outcomes.

Conclusion

The present study showed that CROS adaptation was associated with reduced participation restriction and improved secondary-task accuracy during dual-task performance in individuals with severe-to-profound unilateral hearing loss. Listening effort differed significantly between pre- and post-CROS conditions when assessed by the number of correct responses, but not when assessed by response time. CROS adaptation was also associated with improvements in the physical, psychological, social relationships, and environment domains of the WHOQOL-BREF, although no significant changes were observed in overall quality of life or general health satisfaction. Age was associated with secondary-task accuracy but not response time, suggesting that age should be considered when interpreting dual-task performance in this population.

References

1. Brasil. Pesquisa Nacional de Saúde: 2019: Ciclos de Vida. Ministério da Saúde; 2021.

2. Golub JS, Lin FR, Lustig LR, Lalwani AK. Prevalence of adult unilateral hearing loss and hearing aid use in the United States. Laryngoscope. 2018;128(7): 1681-1686. doi: 10.1002/lary.27017

3. Gouveia FN, Jacob-Corteletti LCB, Silva BCS, et al. Perda auditiva unilateral e assimétrica na infância. Codas. 2020; 32. doi: 10.1590/2317-1782/20192018280

4. Purdy SC, Welch D, Giles E, Morgan CLA, Tenhagen R, Kuruvilla-Mathew A. Impact of cognition and noise reduction on speech perception in adults with unilateral cochlear implants. Cochlear Implants Int. 2017; 18(3): 162-170. doi:10.1080/14670100.2017.1299393

5. Snapp HA, Holt FD, Liu X, Rajguru SM. Comparison of Speech-in-Noise and Localization Benefits in Unilateral Hearing Loss Subjects Using Contralateral Routing of Signal Hearing Aids or Bone-Anchored Implants. Otology & Neurotology. 2017; 38(1). doi: 10.1097/MAO.0000000000001269

6. Snapp HA, Ausili SA. Hearing with One Ear: Consequences and Treatments for Profound Unilateral Hearing Loss. J Clin Med. 2020; 9(4). doi:10.3390/jcm9041010

7. Bell R, Mouzourakis M, Wise SR. Impact of unilateral hearing loss in early development. Curr Opin Otolaryngol Head Neck Surg. 2022; 30(5). doi: 10.1097/MOO.0000000000000848

8. American Academy of Audiology. Adult Patients with Severe-to-Profound Unilateral Sensorineural Hearing Loss. American Academy of Audiology. 2015. Available: https://www.audiology.org/wp-content/uploads/2022/09/PractGuidelineAdultsPatientsWithSNHL.pdf

9. Lefeuvre J, Gargula S, Boulet M, Potier M, Ayache D, Daval M. Active TriCROS: A simultaneous stimulation with a (bi) CROS system and a hearing aid in the worst ear for severely asymmetrical hearing loss. Otology & neurotology. 2024; 45(5): 482-488. doi:10.1097/MAO.0000000000004173

10. Takaki K, Kashio A, Nozaki E, et al. A randomized crossover study in single-sided deafness comparing a cartilage conduction CROS system and an air-conduction CROS system. Otology & neurotology. 2024; 45(6): 635-642. doi:10.1097/MAO.0000000000004199

11. Souza VC, Lemos SMA. Restrição à participação de adultos e idosos: associação com fatores auditivos e socioambientais. Codas. 2021; 33(6): e20200212. doi:10.1590/2317-1782/20202020212

12. Jilla AM, Johnson CE, Danhauer JL, et al. Predictors of hearing aid use in the advanced digital era: An investigation of benefit, satisfaction, and self-efficacy. J Am Acad Audiol. 2020; 31(2): 87-95. doi:10.3766/jaaa.18036

13. Picou EM, Davis H, Lewis D, Tharpe AM. Contralateral routing of signal systems can improve speech recognition and comprehension in dynamic classrooms. J Speech Lang Hear Res. 2020; 63(7): 2468-2482. doi:10.1044/2020_JSLHR-19-00411

14. Sano H, Okamoto M, Ohhashi K, Iwasaki S, Ogawa K. Quality of life reported by patients with idiopathic sudden sensorineural hearing loss. Otology & neurotology. 2013; 34(1): 36-40. doi:10.1097/MAO.0b013e318278540e

15. Ryu NG, Moon IJ, Byun H, et al. Clinical effectiveness of wireless CROS (contralateral routing of offside signals) hearing aids. Eur Arch Otorhinolaryngol. 2015; 272(9): 2213-2219. doi:10.1007/s00405-014-3133-0

16. Lucas L, Katiri R, Kitterick PT. The psychological and social consequences of single-sided deafness in adulthood. Int J Audiol. 2018; 57(1): 21-30. doi:10.1080/14992027.2017.1398420

17. Nguyen DL, Valentin O, Lehmann A, Prévost F. A multimodal investigation of listening effort in single-sided deafness. Am J Audiol. 2024; 33(4): 1341-1349. doi:10.1044/2024_AJA-24-00073

18. Leterme G, Bernardeschi D, Bensemman A, et al. Contralateral routing of signal hearing aid versus transcutaneous bone conduction in single-sided deafness. Audiol Neurootol. 2015; 20(4): 251-260. doi:10.1159/000381329

19. Choi JE, Ma SM, Park H, Cho YS, Hong SH, Moon IJ. A comparison between wireless CROS/BiCROS and soft-band BAHA for patients with unilateral hearing loss. PLoS One. 2019;14(2): e0212503. doi: 10.1371/journal.pone.0212503

20. Gagné JP, Besser J, Lemke U. Behavioral assessment of listening effort using a dual-task paradigm. Trends Hear. 2017; 21: 2331216516687287. doi:10.1177/2331216516687287

21. Holman JA, Drummond A, Naylor G. Hearing aids reduce daily-life fatigue and increase social activity: A longitudinal study. Trends Hear. 2021; 25: 23312165211052784. doi:10.1177/23312165211052786

22. Huang H, Oosthuizen I, Picou EM. Dual-task paradigm measures of listening effort: To include or not to include secondary task responses with incorrect primary task responses. Semin Hear. 2023; 44(2): 155-165. doi:10.1055/s-0043-1766140

23. Degeest S, Kestens K, Keppler H. Listening effort measured using a dual-task paradigm in adults with different amounts of noise exposure. Ear Hear. 2022; (3): 899-912. doi:10.1097/AUD.0000000000001138

24. Gorecka MM, Vasylenko O, Rodríguez-Aranda C. Dichotic listening while walking: A dual-task paradigm examining gait asymmetries in healthy older and younger adults. J Clin Exp Neuropsychol. 2020; 42(8): 794-810. doi:10.1080/13803395.2020.1811207

25. Kwak C, Han W. Age-related difficulty of listening effort in elderly. Int J Environ Res Public Health. 2021;18(16): 8845. doi:10.3390/ijerph18168845

26. Rosemann S, Thiel CM. The effect of age-related hearing loss and listening effort on resting state connectivity. Sci Rep. 2019; 9(1): 2337. doi:10.1038/s41598-019-38816-z

27. Kestens K, Degeest S, Keppler H. The effect of cognition on the aided benefit in terms of speech understanding and listening effort obtained with digital hearing aids: A systematic review. Am J Audiol. 2021; 30(1): 190-210. doi:10.1044/2020_AJA-20-00019

28. Picou EM, Ricketts TA, Hornsby BWY. How hearing aids, background noise, and visual cues influence objective listening effort. Ear Hear. 2013; 34(5): e52-64. doi:10.1097/AUD.0b013e31827f0431

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