Auditory Processing Performance of the Middle-Aged and Elderly: Auditory or Cognitive Decline?

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Abstract

Background: Despite the well-established relationship between aging and auditory processing decline, identifying the extent to which age effect is the main factor on auditory processing performance remains a great challenge due to the co-occurrence of age-related hearing loss and age-related cognitive decline as potential confounding factors.

Purpose: To investigate the effects of age-related hearing loss and working memory on the clinical evaluation of auditory processing of middle-aged and elderly.

Research Design: Cross-sectional study.

Study Sample: A total of 77 adults between 50 and 70 yr of age were invited to participate in the study.

Data Collection and Analysis: The participants were recruited from a larger study that focused on the assessment and management of sensory and cognitive skills in elderly participants. Only participants with normal hearing or mild-to-moderate age-related hearing loss, with no evidence of cognitive, psychological, or neurological conditions were included. Speech-in-noise, dichotic digit, and frequency pattern tests were conducted as well as a working memory test. The hearing loss effect was investigated using an audibility index, calculated from the audiometric threshold. The performance on the digit span test was used to investigate working memory effects. Both hearing loss and working memory effects were investigated via correlation and regression analyses, partialling out age effects. The significance level was set at $p < 0.05$.

Results: The results demonstrated that, while hearing loss was associated to the speech-in-noise performance, working memory was associated to the frequency pattern and dichotic digit performances. Regression analyses confirmed the relative contribution of hearing loss to the variance in speech-in-noise and working memory test to the variance in frequency pattern and dichotic digit test performance.

Conclusions: The performance decline of the elderly in auditory processing tests may be partially attributable to the working memory performance and, consequently, to the cognitive decline exhibited by this population. Mild-to-moderate hearing loss seems to affect performance on specific auditory processing tasks, such as speech in noise, reinforcing the idea that auditory processing disorder in the elderly might also be associated to auditory peripheral deficits.

Key Words: cognition, elderly, hearing

Abbreviations: AI = audibility index; DDT = dichotic digit test; FPT = frequency pattern test; SNT = speech-in-noise test; SRT = speech recognition threshold

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INTRODUCTION

Research has demonstrated that as part of the natural aging process, elderly (Fitzgibbons and Gordon-Salant, 1996; Pichora-Fuller and Souza, 2003; Anderson et al, 2012; Moore et al, 2012; Füllgrabe, 2013; Schoof and Rosen, 2014) and occasionally middle-aged people (Grose et al, 2006; Moore et al, 2014) exhibit performance decline in tasks involving different auditory processing skills, such as speech perception in noise (Humes et al, 2013; Schoof and Rosen, 2014; Füllgrabe et al, 2015), temporal resolution (Pichora-Fuller and Souza, 2003; Gallun et al, 2014), and dichotic listening (Grose, 1996; Füllgrabe, 2013). Therefore, a test battery is recommended for the diagnosis of auditory processing disorder, including a speech-in-noise test (SNT) as well as auditory temporal and dichotic listening tests, to investigate the extent to which each specific auditory skill is impaired and which skills should be addressed by rehabilitation.

Despite this well-established relationship between auditory processing decline and aging, identifying the extent to which the age effect is the main factor accounting for the degraded auditory processing performance remains a challenge due to co-occurrence of other confounding factors such as age-related hearing loss (Davis, 1991; Cruickshanks et al, 1998) and age-related cognitive decline (De Beni and Palladino, 2004; Craik and Rose, 2012; Grady, 2012). Moreover, several studies have noted the increased risk for co-occurrence of auditory disorders, such as presbycusis and auditory processing disorder, with cognitive decline, including mild cognitive impairment and even dementia (Peters et al, 1988; Baltes and Lindenberger, 1997; Avila et al, 2014; Panza et al, 2015; Wayne and Johnsrude, 2015) This co-occurrence highlights the difficulty in understanding sensory–cognitive interactions, particularly from the clinical perspective. Auditory sensory aspects that underpin the peripheral auditory function include pure-tone sensitivity as well as frequency selectivity, temporal coding fidelity, intensity resolution, and loudness (Wayne and Johnsrude, 2015). Cognitive aspects that influence central auditory functions include different skills involving language, memory, and other cognitive abilities such as general reasoning, processing speed, selective attention, and other executive functions (Wayne and Johnsrude, 2015).

Several studies attempt to disentangle the effects of age and peripheral hearing loss on auditory processing by comparisons between age-matched groups of elderly with normal hearing and hearing impairment (Leigh-Paffenroth and Elangovan, 2011; John et al, 2012; Sheft et al, 2012) or by correlation between the audiometric results and the speech recognition performances in elderly groups (Cooper and Gates, 1992). The majority of these studies report detrimental effects of hearing loss on different aspects of auditory processing, such as temporal processing (Leigh-Paffenroth and Elangovan, 2011; John et al, 2012), dichotic listening (Cooper and Gates, 1992; Martin and Jerger, 2005), and speech recognition (Humes and Christopherson, 1991; Humes et al, 2013). However, for the majority of these studies, the co-occurrence of age-related cognitive decline, which may confound auditory processing test performance, has generally not been considered. Additionally, conflicting results regarding the age-related hearing loss effect have also been reported. For example, in a study by Sheft et al (2012), no difference was reported between the performances of nine normal-hearing and nine elderly listeners with mild-to-moderate sensorineural hearing loss in tasks involving stochastic frequency modulation discrimination in background noise. The authors suggested that hearing loss distortion was not a factor that influenced the psychoacoustic performance of these listeners in this task.

Age-related cognitive decline is a well-known confounding factor for auditory processing performance, particularly because of the cognitive-sensory interaction that is observed with aging (Cohen, 1987; Humes et al, 2013; Moore et al, 2014; Füllgrabe et al, 2015). The cognitive aspect that frequently declines in the elderly and is most strongly associated with auditory processing performance is working memory (Pichora-Fuller et al, 1995; Hällgren et al, 2001; Pichora-Fuller, 2003; Akeroyd, 2008; Mukari et al, 2010). According to Pichora-Fuller et al (1995), working memory could be defined as a capacity-limited system in which information can be stored and manipulated using knowledge stored in long-term memory. Studies have demonstrated some degree of correlation between working memory performance and the perception of speech in noise (Pichora-Fuller et al, 1995; Akeroyd, 2008), pitch pattern frequency recognition (Mukari et al, 2010), and dichotic listening (Hällgren et al, 2001). However, conflicting results have also been reported (Mukari et al, 2010; Schoof and Rosen, 2014). For example, Mukari et al (2010) demonstrated a lack of correlation between working memory and the dichotic digit test (DDT) performance of young and older groups when the variable age was controlled. Schoof and Rosen (2014) found that older adults experienced increased difficulties understanding speech only in the presence of two-talker babble; however, this finding was not associated with working memory performance, which suggests that the auditory processing performance was not explained by age-related cognitive decline involving working memory, specifically.

Although studies have demonstrated the effects of hearing loss and working memory on auditory processing performance, few have controlled both aspects in the same experiment. Such investigations are important

because the greater the number of variables that are possibly involved in auditory processing performance, the greater the difficulty in interpreting the results of auditory processing evaluations. Moreover, experimental rather than clinical tests have generally been performed, which confounds the interpretation of the results from a clinical perspective. Therefore, in the present research, the auditory processing test performance of listeners with normal-hearing and mild-to-moderate age-related hearing loss was investigated. The DDT, SNT, and frequency pattern test (FPT) were included in the battery. DDTs are good indicators of central auditory processing disorder (Musiek and Lamb, 1994; Bamiou et al, 2007; Bamiou et al, 2012), allowing investigation into a specific aging process in the central auditory system. The SNT was included because, in general, older adults report increased difficulties understanding speech in challenging listening conditions (Pichora-Fuller and Souza, 2003; Schoof and Rosen, 2014). As an auditory temporal processing test, the FPT is also important not only because of the possible age-related deficits in temporal processing (Humes et al, 2010; Gallun et al, 2014) but also because of the likely relationship between speech perception and temporal processing (Phillips et al, 2000; Pichora-Fuller et al, 2007).

To investigate the hearing loss effect, an Audibility Index (AI) was calculated from the audiometric thresholds, based on the method described by Mueller and Killion (1990). This AI is a useful measure to scale hearing status numerically, allowing for investigation regarding the extent to which different degrees of hearing loss and other measures are correlated (Mueller and Killion, 1990). To investigate the cognitive effect, a working memory test (backward digit span) was conducted. This specific component of cognition was chosen because it is frequently reduced in the elderly and is strongly associated with auditory processing performance (Pichora-Fuller et al, 1995; Hällgren et al, 2001; Pichora-Fuller, 2003; Akeroyd, 2008). The recruited individuals were ≥50 yr of age and the auditory processing tests were those commonly performed in a clinical battery, such as speech-in-noise perception, pitch (frequency) pattern, and DDT.

We predicted that both age-related hearing loss and working memory would impact negatively on the performance on auditory processing tests. Additionally, we predicted the presence of significant sensory–cognitive interaction. From a clinical perspective, we expect the results to contribute to improving the understanding of the diagnoses of auditory processing disorder in middle-aged and elderly populations.

METHODS

Ethics Statement

This study was conducted at the Department of Physical Therapy, Speech-Language Pathology and Occupational Therapy of the School of Medicine at the University of Sao Paulo and was approved by the Research Ethics Committee of the Analysis of Research Projects of the University Hospital Medicine School, University of São Paulo under protocol number CEP-HU/USP: 100511 0-SISNEP CAAE: 0034.0.198.000-10. A written consent form with detailed information about the aim and protocols of the study was also approved by this ethics committee.

Participants

A total of 77 adults, native Brazilian Portuguese speakers, between 50 and 70 yr of age, took part in the study. Participants were selected from a large epidemiological study "Aging maintaining functions: elderly in the 2020s" (Mansur and Carvalho, unpublished project) that focused on the assessment and rehabilitation of sensory and cognitive skills in elderly. All were recruited from the general community by flyer and advertisement posted in public spaces in the city of São Paulo. From this large study, participants were selected based on the inclusion criteria of having no evidence of cognitive, psychological, or neurological conditions investigated by psychologists and neurologists. In terms of cognition, to exclude the presence of cognitive impairments, the participants were required to attain the following cutoff scores, adapted to the participants' educational level, on the Mini-Mental State Exam: >25, >26, or >28 for 1–4 yr, 5–8 yr, and >9 yr of formal schooling, respectively (Folstein et al, 1975; Brucki et al, 2003). In addition, they were also required to not exceed a score of 2 points on the Questionnaire of Cognitive Change (QMC8) (Damin and Brucki, 2011) and a score of 7 points on the American Speech-Language-Hearing Association Functional Assessment of Communication Skills for Adults (de Carvalho and Mansur, 2008). Neurological and psychological aspects were investigated using the Geriatric Depression Scale-15 (Sheikh and Yesavage, 1986; Almeida and Almeida, 1999). In terms of hearing evaluations, the participants underwent otoscopy and audiological assessments including pure-tone threshold audiometry and a speech recognition threshold (SRT) test. Both tests were administered in a Siemens sound-proof booth, calibrated in accordance with ANSI S3.1, using a GSI-61 two-channel clinical audiometer, also calibrated in accordance to ANSI S3.6, used with TDH39 earphones. Normal-hearing listeners and listeners with mild-to-moderate age-related hearing loss were included. Normal hearing was defined as pure-tone threshold audiometry ≤25 dB HL for octave frequencies from 250 to 8000 Hz and the mild-to-moderate age-related hearing loss was defined as bilateral, symmetrical, and sloping hearing loss (pure-tone thresholds ranging from 25 to 70 dB HL at the frequencies of 3–8 kHz). Because most of the auditory processing tests had to be performed at the level of 50 dB SL above SRT (Jerger and Musiek,

2000), individuals with severe hearing loss were not included.

The participant characteristics such as age, educational level, and cognitive screening performance are illustrated in Table 1.

Procedures and Measures

After signing the written consent forms, the participants underwent all auditory processing tests (i.e., the DDT, FPT, and SNT) as well as the working memory test. The tests were chosen as recommended by the AAA (2010) for the diagnosis of auditory processing disorder. Moreover, accounting for the clinical purpose of this study, only tests that had been standardized for the Brazilian population were included. To investigate the influence of age-related hearing loss and working memory on the auditory processing performance, the hearing loss was scaled using the AI and the working memory was assessed using a digit span test.

Auditory Processing Tests

All auditory processing tests were administered in a sound-proof booth using a GSI 61 Audiometer, Sony Compact Disc Player, and headphones. The stimuli, recorded on a compact disc, were played on the CD player connected to the audiometer. This audiometer controlled the stimuli intensity at a fixed level of 50 dB SL in reference to the SRT.

DDT: This central auditory test assesses binaural integration skills (i.e., the ability to process different stimuli that are presented simultaneously to each ear). This Brazilian version of the DDT was composed of naturally spoken dissyllabic digits with similar syllable lengths; specifically, 4, 5, 7, 8, and 9 were used. The digits were spoken in Portuguese by a male speaker. The test included 20 trials. Each trial consisted of two pairs of digits presented simultaneously (with one pair of the two routed to each ear). The individual was instructed to listen carefully and repeat both pairs of digits at the end of each trial. In total, the test included 40 pairs of digits (80 digits per ear). Performance was scored according to the percentage of correctly repeated digits in each ear, irrespective of the order (Pereira and Schochat, 1997).

Table 1. Group Characteristics

Variables	Mean ± SD	Minimum/Maximum
Gender (n)		
Female	52	
Male	25	
Age	60.3 ± 5.4	50/74
Years of formal schooling	11.7 ± 4.7	3/24
Audiological evaluation		
SRT (dB HL)		
RE	16.4 ± 4.7	5/35
LE	16.6 ± 5.2	5/30
Cognitive screening		
MMSE	28.3 ± 1.3	25/30

Note: LE = left ear; MMSE = Mini-Mental State Exam; RE = right ear; SD = standard deviation.

SNT: This central auditory test assesses the ability to understand speech in a background of noise. This Brazilian version of the SNT was composed of 25 monosyllabic words spoken in Portuguese by a male speaker that were presented to each ear at a fixed signal-to-noise ratio of +20 dB. The background noise was white noise. The individual was instructed to carefully listen to each of the words and then repeat them. Performance was measured according to the percentage of correctly repeated words that were presented to each ear. This test was administered in a sound-attenuating booth at 50 dB SL relative to the SRT (Pereira and Schochat, 1997).

FPT: This central auditory test assessed skills related to auditory temporal processing (i.e., the ability to process nonverbal auditory signals and recognize the order or pattern of the presentation of these stimuli). This test consisted of 20 trials with ~6-sec intertrial intervals. Each trial included three stimuli of 150 msec in duration and an interstimulus interval of 200 msec. The low stimulus (L) was 880 Hz, and the high stimulus (H) was 1122 Hz. The individual was instructed to carefully listen to all three stimuli and to respond by naming them in the order in which they were presented (e.g., "low, low, high," "high, low, low," etc.). Performance was measured according to the percentage of correct trials. This test was administered diotically in a sound-attenuated booth at 50 dB SL relative to the SRT (Musiek and Pinheiro, 1987).

Working Memory Test

Digit Span (Backward Recall): This test was taken from the Wechsler Adult Intelligence Scale test to investigate the extent at which auditory processing and cognitive performance were associated. In this working memory test, participants were instructed to verbally repeat a sequence of numbers, also presented verbally, in reverse order. The number of digits in the sequence was gradually increased until the participant could not repeat them correctly. The digit span performance was taken as the number of digits for the longest list of numbers repeated accurately (Wechsler, 1987).

AI

The AI is a useful measure to scale hearing status numerically, and thus facilitate correlational analysis for

degree of hearing loss and other measures. The calculation method was described by Mueller and Killion (1990) and used in a previous study (John et al, 2012). The index is calculated on the basis of the air-conduction thresholds and uses the count-the-dot method, in which different frequencies are weighed according to their importance for understanding speech. This index number thus indicates the audibility of a typical speech signal for the measured ear and ranges from 0 to 1.0.

Statistical Analyses

The data were analyzed using SPSS version 22.0. Pearson's correlation and stepwise multiple regression were calculated to determine the strength of the association between hearing loss, working memory, and auditory processing performance. More details about each analysis are described further. The significance level was set at $p < 0.05$.

RESULTS

Correlations between Auditory Processing, Working Memory, and Hearing Loss

Performance results for the auditory processing and working memory tests, as well as the AI for each ear, are listed in Table 2.

First, the association between these performances was assessed to investigate the extent to which the performances on auditory processing tests were associated to either working memory performance or hearing loss. The correlation between auditory processing test performances and working memory was assessed, partialling out the effect of age, gender, education, and hearing. The correlation between auditory processing performances and hearing loss was assessed, partialling out the effect of age, gender, education, and working memory. Significant correlation coefficients ($p < 0.05$) are shown in black in Table 3.

Table 2. AI, Auditory Processing, and Working Memory Performance

Tests/Variables	Mean ± SD
AI	
RE	0.93 ± 0.1
LE	0.91 ± 0.1
Auditory processing tests	
DDT (%)	
RE	94.4 ± 5.3
LE	91.4 ± 7.5
SNT (%)	
RE	88.1 ± 7.4
LE	91.7 ± 6.4
FPT (%)	55.8 ± 23.2
Working memory test	
Digit span (backward)	3.8 ± 1.1

Note: LE = left ear; RE = right ear; SD = standard deviation.

DDT

Partial correlations showed a weak to moderate association between digit span performance in the right ear on dichotic digit ($r_{\text{partial}} = 0.30, p < 0.01$) and a tendency toward significance association between digit span and the left ear ($r_{\text{partial}} = 0.20, p = 0.09$). No significant correlations were observed between AI and DDT performance.

SNT

No significant correlations were observed between the SNT (both ears) and digit span tests (see Table 3). Regarding hearing loss, partial correlations showed a moderate association between AI in the right ear and speech-in-noise performance in this same ear ($r_{\text{partial}} = 0.49$, $p < 0.01$). The same results were obtained between the AI in the left ear and speech-in-noise performance in this same ear ($r_{\text{partial}} = 041$, $p < 0.01$). A weak to moderate association was found between AI and speech-in-noise performance, AI (left ear) and speech-in-noise (right ear) ($r_{\text{partial}} = 034$, $p < 0.01$), and AI (right ear) and speech-in-noise (left ear) ($r_{\text{partial}} = 038$, $p < 0.01$).

FPT

Partial correlations showed a moderate association between performance on the digit span and FPT ($r_{\text{partial}} = 0.43$, $p < 0.001$). No significant correlations were observed between AI and FPT performance.

Figure 1 shows the significant correlations between the AI and speech-in-noise performance in both ears. Figure 2 shows the correlations between working memory and frequency pattern as well as working memory and dichotic digit performance in the right ear. The figures also show the significant coefficients for the whole group.

To investigate sensory–cognitive interactions, the strength of the association between working memory and hearing loss was also assessed, partialling out age and education. No significant correlation was observed between AI and digit span performance.

Stepwise Multiple Regression

Multiple regression analyses (stepwise method) were performed to investigate the relative contribution of hearing loss and working memory to the variance in the auditory processing tests. AI, working memory, and age were considered as predictor variables.

Table 3. Correlations between Hearing Loss, Memory, and Auditory Processing Performance

Tests/Variables	Hearing (Controlled for Age, Gender, Memory, and Education) RE	Hearing (Controlled for Age, Gender, Memory, and Education) LE	Memory (Controlled for Age, Gender, Hearing, and Education)
Auditory processing			
Dichotic digit (%)			
RE	−0.11	−0.15	**0.30**
LE	−0.05	0.06	*0.20*
Speech-in-noise (%)			
RE	**0.49**	**0.34**	0.03
LE	**0.38**	**0.41**	0.01
Frequency pattern (%)	−0.20	−0.11	**0.43**

Notes: Values in bold are significant, italic are tendency to significance, and regular are nonsignificant. LE = left ear; RE = right ear.

For the speech-in-noise performance in the right ear, the model that explained the highest percentage (18%) of the variance was based on only the AI in the same ear [$F_{(1,76)} = 16.6, p < 0.001$]. The standard regression coefficient was 0.42 ($p < 0.001$). For the speech-in-noise performance in the left ear, the best model also included AI in the same ear as the best predictor, which explained 16% of the variance [$F_{(1,76)} = 14.3$, $p < 0.001$]. The standard regression coefficient was 0.40 ($p < 0.001$).

For the frequency pattern performance, the best model included working memory as the best predictor, which explained 17% of the variance [$F_{(1,73)} = 14.7$, $p < 0.001$]. The standard regression coefficient was 0.41 ($p < 0.001$). Working memory was also the best predictor for the DDT in the right ear, but explained

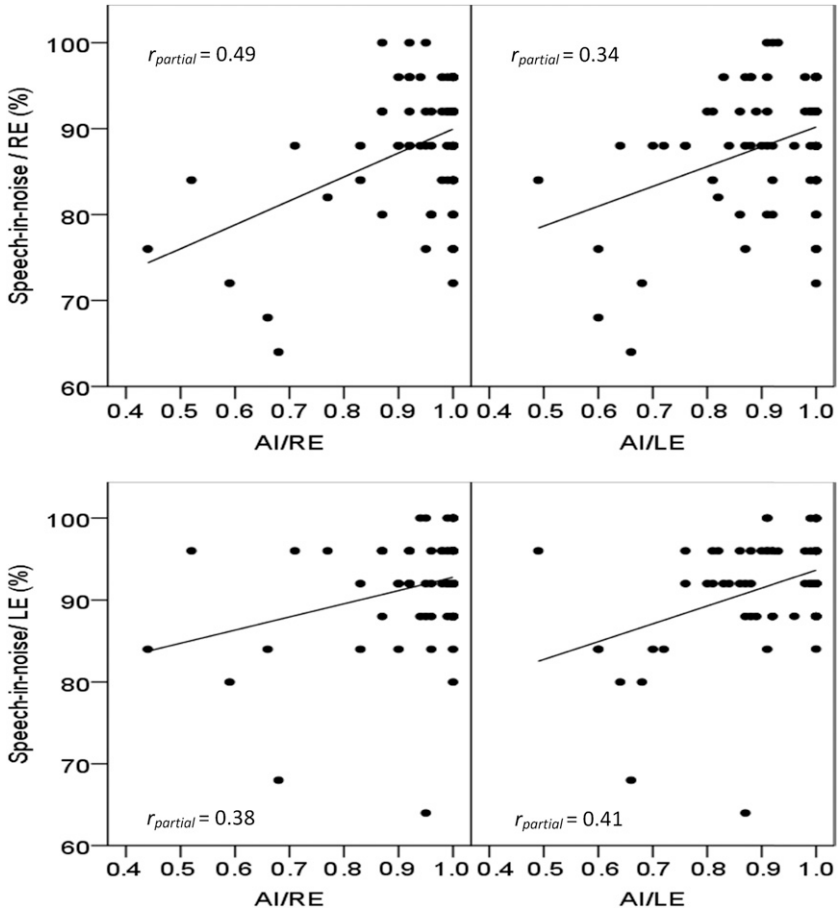

Figure 1. Correlations between the AI and speech-in-noise performance in both ears. Each dot represents an individual participant and the black line represents the best linear fit to the data from the entire group. LE = left ear; RE = right ear.

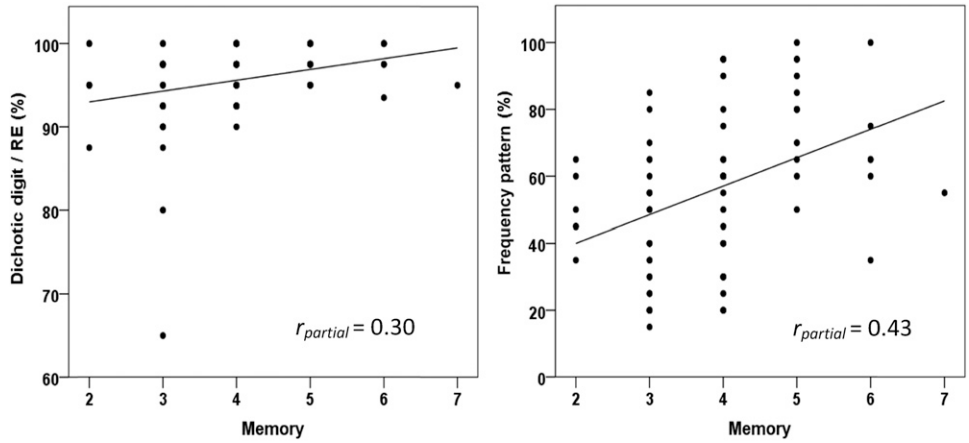

Figure 2. Correlations between working memory and dichotic digit performance in the right ear as well as working memory and frequency pattern performance. Each dot represents an individual participant, and the black line represents the best linear fit to the data from the entire group.

only 7% of the variance [$F_{(1,76)} = 5.89$, $p = 0.01$]. The standard regression coefficient was 0.27 ($p = 0.01$).

For the dichotic digit performance in the left ear, working memory, hearing, and even age did not significantly contribute to variance on performance.

DISCUSSION

The main purpose of the present research was to investigate the effects of age-related hearing loss and working memory on the auditory processing performance of middle-aged and elderly participants to better interpret the results of auditory processing evaluations. The results demonstrated that hearing loss was associated to the SNT performance, whereas working memory was associated with the FPT and DDT performance. No association was found between hearing loss and working memory. The average test scores of the group, although high, were slightly below the expected average scores for young Brazilian adults (Pereira and Schochat, 1997). Mean test scores are reported to be 95% in each ear in the DDT, 70% in the SNT, and 75% in the FPT. Previous studies have also demonstrated that the performance of older adults on the DDT (Luz and Pereira, 2000), FPT (Parra et al, 2004), and SNT (Pereira and Schochat, 2011) are below the performance of young individuals. This finding is consistent with previous research, reinforcing the idea that the decline presented here was associated with aging. The observation of only a slight decline was potentially due to the inclusion of middle-aged individuals, who might still have demonstrated good performance on the clinical auditory processing tests.

The effect of hearing loss on SNT performance corroborates several studies' findings (Humes and Christopherson, 1991; Cooper and Gates, 1992; Martin and Jerger, 2005; Leigh-Paffenroth and Elangovan, 2011; John et al, 2012; Humes et al, 2013) and also supports the peripheral hypothesis regarding the auditory processing difficulties of the elderly (Humes et al, 2012). According to this hypothesis, auditory difficulties, such as those related to understanding speech in background noise and discriminating temporal changes in auditory stimuli, are predominantly the consequence of the loss of audibility associated with age-related hearing loss. Thus, loss of hearing can lead to an interaction between central and peripheral auditory deficits. Additionally, research has also demonstrated that the hearing loss effect might be more prominent for some specific auditory tasks versus others (Humes et al, 2012; Sheft et al, 2012). For example, in an extensive review of central presbycusis, Humes et al (2012) concluded that hearing loss generally has greater influences on auditory test measures that involve understanding speech than on tasks involving nonspeech stimuli, such as demonstrated in the present research. The explanation for this observation is that the broadband nature of speech signals requires reasonable audibility over at least 4000 Hz for discrimination (Humes et al, 2012). In contrast, nonspeech stimuli are easier to discriminate if they are composed of frequencies in the range of normal hearing. For example, Sheft et al (2012) reported no hearing loss effects on a task involving the discrimination of frequency modulations, with a carrier frequency of 1 Khz presented in background noise for elderly listeners with normal hearing or a mild-to-moderate sensorineural hearing loss. Similarly, in the present study, the FPT included low and high stimuli at frequencies of 880 Hz and 1122 Hz, respectively. Furthermore, the lack of a hearing loss effect on the nonverbal tests might be explained by the presence of normal hearing (or only a mild hearing loss) in the frequency range of the test stimuli. Therefore, the present results confirmed that hearing loss might affect the performance in tests involving speech recognition in a background noise,

probably due to the broadband nature of speech signals. From a clinical perspective, these results suggest that auditory processing test deficits in the middle-aged and elderly with mild-to-moderate hearing loss might be associated with auditory peripheral deficits.

Working memory effects were observed in the FPT and DDT. Additionally, a stronger correlation was observed between the working memory and FPTs ($r = 0.43$) than between the working memory and DDTs ($r = 0.30$), which suggests that the cognitive demand in the FPT was probably greater than that in the DDT. The FPT requires the individual to not only carefully attend to the sounds but also to associate each sound with an oral response, stored within memory, and act on the association when speaking the correct answer (Moore, 2012). Thus, this association between sound and oral response probably explains why a stronger correlation was observed in the FPT than the DDT, the latter of which does not require such associations. Additionally, in the FPT, the individual is also required to memorize the stimuli sequence to respond correctly, whereas in the DDT the individual can repeat irrespective of the order, which probably reduces the cognitive demand of the test.

Mukari et al (2010) also observed an association between temporal ordering and working memory performance. As in the present study, these authors reported a moderate correlation between the performances in the digit span test and the Pitch Pattern Sequence test. The authors point out that a positive correlation between working memory is expected as the correct response on the FPT is scored on the correct labeling of the tonal sequence. Mukari et al explain in detail how interpretation of patterns and identification occur in the right hemisphere and then this tonal sequence must be conveyed to the left hemisphere via the corpus callosum where verbal labeling takes place. Thus, the test is less related to specific auditory modality.

Mukari et al (2010) also investigated the correlations between performance on the DDT and working memory among older adults. Contrary to the present findings, these authors observed no correlation between DDT and working memory when the effect of age was partialized out. Hällgren et al (2001) demonstrated a correlation between the performance in the digit span test and a free-report condition of the DDT in the elderly; however, their results were also associated with an effect of age. This cognitive influence on dichotic listening test performance has been extensively studied by Hughdal and colleagues in children and young adults (Hugdahl and Andersson, 1986; Hugdahl et al, 2001; Hugdahl, 2003), and the results have demonstrated greater cognitive engagement in the forced-left condition that is produced by competition with the "right ear advantage." In the present study, after controlling for an age effect, a cognitive effect was observed even in the free recall condition, albeit this effect is only weak to moderate ($r = 0.30$) in the right ear with a tendency to significance in the left ear ($r = 0.20$, $p = 0.09$). Therefore, from a clinical perspective, in addition to aging effects, the performance of the middle aged and elderly in the FPT and DDT might be also associated, at least partially, with some degree of cognitive decline rather than with pure age-related auditory processing decline.

In the present study, we also observed a lack of association between working memory and the performance on the SNT. Current findings are consistent with previous work investigating associations between working memory and speech perception in noise (Schoof and Rosen, 2014). Indeed, in this study, no association was found between performance of elderly individuals on working memory and speech perception tasks for words in the presence of two-talker babble. These results suggest that age-related cognitive decline, involving specifically working memory, does not necessarily lead to speech-in-noise problems. However, association between working memory and speech perception in noise has also been reported (Pichora-Fuller et al, 1995; Akeroyd, 2008). Pichora-Fuller (2003) hypothesized that, as a consequence of hearing difficulties and the effort required to listen in the presence of noise, the efficient operation of the working-memory system becomes compromised and negatively affects the comprehension of spoken language. Perhaps the controversies regarding the influence of working memory on speech perception are related to the type of speech that is used in the noise task because more complex speech perception tasks might demand more cognitive engagement. Thus, tasks involving single words, such as those used in the present research, are likely less cognitively demanding than tasks that involve sentences, such as those used in the study by Pichora-Fuller et al (1995). From a clinical perspective, the absence of working memory effects on the speech-in-noise task performance indicates that the worse performance exhibited by the elderly might likely be interpreted as a result of elevated thresholds and not attributable to cognitive changes.

Previous research has shown a strong connection between age-related decline in working memory and problems with auditory performance (Peters et al, 1988; Baltes and Lindenberger, 1997; Panza et al, 2015; Wayne and Johnsrude, 2015). No association was found in the current study between working memory and the AI. Perhaps this lack of interaction was due to the fact that only one specific component of cognition was assessed (working memory). Thus, further studies should investigate sensory–cognitive interaction using additional cognitive measures. Another hypothesis is related to the level of hearing loss and participant selection methods. Perhaps a mild-to-moderate hearing loss may not be sufficient to be associated with working memory performance.

Few studies have investigated the effects of age-related hearing loss and working memory on auditory processing test performance in the same study. The present results demonstrated that even after controlling for age, performance on the auditory processing tests, such as the FPT and DDT, was affected by an aspect of cognition while SNT performance was affected by hearing levels. Our results demonstrated that from a clinical perspective, the poor performance of older adults in tests of auditory processing might not be specifically attributable to auditory recognition and processing decline. Poor performance might be partially attributable to working memory limitations and consequently to the cognitive decline exhibited by this population. Mild-to-moderate hearing loss seems to affect the performance on specific auditory processing skills, such as speech-in-noise, reinforcing the idea that auditory processing disorder is also linked to auditory peripheral deficits in the elderly.

Since the present results demonstrate that some clinical auditory processing tests show high cognitive demand, a careful evaluation of elderly participants' cognitive skills, such as working memory, is essential before interpreting their performance on auditory processing tests. Additionally, both the degree and configuration of the hearing loss must also be taken into consideration especially when considering results of auditory processing tests involving verbal stimuli. Further studies should focus on the development of clinical auditory processing tests with low cognitive demand to reduce the impact of confounding factors such as age-related cognitive decline.

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