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Article Title: The impact of aging and hearing status on verbal short-term memory

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Word count for abstract: 125 words

Word count for manuscript: 5144 words

Abstract

The aim of this study is to assess the impact of hearing status on age-related decrease in verbal short-term memory (STM) performance. This was done by administering a battery of verbal STM tasks to elderly and young adult participants matched for hearing thresholds, as well as to young normal-hearing control participants. The matching procedure allowed us to assess the importance of hearing loss as an explanatory factor of age-related STM decline. We observed that elderly participants and hearing-matched young participants showed equal levels of performance in all verbal STM tasks, and performed overall lower than the normal-hearing young control participants. This study provides evidence for recent theoretical accounts considering reduced hearing level as an important explanatory factor of poor auditory-verbal STM performance in older adults.

Keywords: aging, hearing status, verbal short-term memory, auditory processing, storage capacity

Short-term memory (STM) decline in older adulthood has been well documented (e.g., Bopp & Verhaeghen, 2005; Hale et al., 2011; Maylor, Voudsen, & Brown, 1999). The present study assesses the role of auditory-sensory status as an explanatory factor of poor STM in older adults, and this specifically in the auditory-verbal modality. Most of previous research related STM decline to multiple cognitive factors such as a slowed speed of processing (e.g., Salthouse, 1996), a lack of inhibitory control (e.g., Persad, Abeles, Zacks, & Denburd, 2002), increased sensitivity to interference (e.g., Oberauer & Kliegl, 2001), or context-item binding deficits (e.g., Oberauer, 2005). However, the role of sensory variables such as hearing status on cognitive performance was often given no consideration. Surprenant (2007) noted that, although one-third of adults above 70 years of age have a significant hearing loss and that almost 100 percent of the elderly have some mild hearing loss (e.g., Cruickshanks et al., 1998), less than 25 percent of researchers investigating cognitive aging have considered auditory acuity as a factor in their experiments. This comment is particularly crucial for verbal STM tasks, which typically consist in the auditory presentation of lists of verbal items for immediate serial recall.

A number of studies have shown a strong association between sensory status and cognitive functioning such as the seminal studies by Lindenberger and Baltes (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Lindenberger & Ghisletta, 2009). The authors observed strong correlations between vision and hearing status and cognitive functioning, including measures of STM capacities, with correlations increasing with age (however, see Rönnberg et al. (2011) who showed a selective impact of hearing loss on episodic and semantic long-term memory (LTM) tasks but not on STM tasks).

By contrast, a great number of authors indicated that hearing loss may directly interfere with STM performance (e.g., Baldwin & Ash, 2011; Cervera, Soler, Dasi, & Ruiz, 2009; McCoy et al., 2005; Murphy, Craik, Li, & Schneider, 2000; Pichora-Fuller, Schneider,

& Daneman, 1995; Schneider & Pichora-Fuller, 2000; Rabbit, 1991; van Boxtel et al., 2000). McCoy et al. (2005) and Rabbit (1991) showed that elderly participants with mild auditory impairment recalled fewer words than elderly participants without hearing loss. In order to distinguish the effects of hearing loss from the effects of aging on STM performance, some authors simulated the effect of age-related hearing loss on younger participants STM performance by lowering the auditory output level during stimulus presentation (e.g., Baldwin & Ash, 2011) or by adding a background noise to the presentation of memoranda (e.g., Murphy et al., 2000; Pichora-Fuller et al., 1995). Baldwin and Ash showed that both young and older participants recalled fewer items for items presented at lower auditory amplitude. Moreover, Murphy et al. as well as Pichora-Fuller et al. indicated that recall performance decreased for both young and older participants when a background noise was added. At the same time, the manipulations used in the aforementioned studies did not remove the age effects in the STM tasks. Pichora-Fuller et al., however, further showed that when presenting items visually on a verbal STM task, no age differences were observed. Although visual and auditory STM tasks may differ on a number of dimensions (presentation speed, perceptual analysis speed, sequential versus simultaneous item processing), these results suggest that auditory impairment may explain age-effects on STM performance to some extent. The studies by Cervera et al. (2009) and van Boxtel et al. (2000) further suggested a role of auditory impairment in age-related STM decline: they observed that age-related differences on STM performance became non-significant when controlling for hearing thresholds via statistical procedures such as analyses of covariance or partial correlations.

A stronger and more direct test of the importance of hearing loss as an explanatory factor of age-related STM decline would however be the comparison of young and elderly participants directly matched for hearing level. The advantage of this procedure is that no experimental manipulation of stimulus audibility is needed and that the impact of hearing status on STM performance can be determined directly rather than indirectly via statistical control procedures. This was the aim of the present study by comparing elderly participants with a reduced hearing level to young adult participants matched for hearing level, as well as to young adult participants with no reduced hearing level. To our knowledge, a few studies have used this approach while exploring memory tasks. In the study of Wingfield, McCoy, Peelle, Tun, and Cox (2006), young and older participants matched for hearing thresholds were presented an auditory comprehension task of syntactically simple short sentences. The authors showed that both groups performed equally and performed overall lower than young and elderly participants with normal hearing levels, indicating thus that hearing status may be an important explanatory factor of age-related drop in auditory-verbal cognitive tasks. However, although STM abilities are likely to be involved in the sentence comprehension task used by Wingfield et al., this study does not yet directly demonstrate that age-related STM decline is related to age-related hearing loss.

Tun, McCoy, and Wingfield (2009) compared old mildly auditory impaired participants to young hearing-matched participants on an auditory serial recall task of words. On this task, the participants were asked to count aloud by threes during a 30s-delay. The authors observed that the young participants still outperformed the older participants. However, the persistence of age effects in this study is difficult to interpret. First, the use of a secondary task during the maintenance delay will recruit additional executive processes during task processing which are known to be impaired in elderly participants (e.g., Brink & McDowd, 1999; Gaeta, Friedman, Ritter, & Cheng, 2001; Kane, May, Hasher, Rahhal, & Stoltzfus, 1997; Milham et al., 2002). Second, given that the participants had to retrieve the words after a 30-s delay, it is likely that this task has already recruited episodic long-term memory. For example, Öztekin, Davachi, and McElree (2010) examined neural activation during a 12-item probe-recognition task and observed that the hippocampus, involved in episodic memory processes, was activated for retrieval of all serial positions except for the most recent ones. Age-related episodic memory difficulties have been widely documented (e.g., Balota, Dulan, & Duchek, 2000; Burke & MacKay, 1997; Rönnberg et al., 2011) and may have played a role in the results obtained in the study of Tun et al.

In the present study, we used standard immediate serial recall and reproduction tasks for auditorily presented verbal information probing specifically and directly auditory short-term retention abilities, by avoiding any contamination by concurrent executive processing demands. These 'passive' immediate serial recall tasks used here simply required the decoding and short-term maintenance of auditorily presented memoranda, and at the executive level of processing required simple attentional focalization processes which are known to be preserved in elderly populations (Oberauer, 2001). We also tried to minimize the intervention of episodic memory processes by testing recall immediately after list presentation. Finally, in order to control for the possibility that impaired performance in hearing impaired groups could be simply explained by the fact that items were misperceived during encoding, we further assessed online phonological processing via a speeded single nonword repetition task with low STM load.

Method

Participants

Three groups of participants took part in this study: (1) 16 elderly adults (mean age=69.94 years; *SD*=5.56), (2) 16 young adults with a reduced hearing level (mean age=25.17 years; *SD*=5.47), matched to the elderly for auditory threshold and (3) 16 young adult control participants with normal hearing status (mean age=24.15 years; *SD*=1.39). All participants were recruited from local community via announcements. Because our aim was to directly assess the effects of hearing status on verbal STM performance, we aimed at matching young and older participants on hearing thresholds. First, we began by selecting young participants with and without reduced hearing levels. Their auditory acuity was measured via pure-tone audiometry for 250, 500, 1000, 2000, 3000 and 4000 Hertz (Hz) frequency tones presented to the right and left ear. Young participants were assigned to one of the two young adult participant groups depending on hearing status; young participants were screened until a sufficient number of participants for each group was reached, following a ‘first come first served’ principle. Then we selected older participants who were matched with the mildly hearing impaired young participants for hearing thresholds, meaning that older participants with more severe hearing loss than the young participants with reduced hearing levels were excluded from participation to this study. Bilateral mean pure-tone audiometry thresholds and standard deviations per frequency, i.e., 250, 500, 1000, 2000, 3000 and 4000 Hz are presented in Table 1. We performed a mixed ANOVA with a 3 (group: young adult controls, young adults with a reduced hearing level, older adults) by 6 (frequency: 250, 500, 1000, 2000, 3000 and 4000 Hz) analysis design. This analysis revealed a significant group effect, $F(2,45)=41.67$, $MSE=105.76$, $p<.001$, $\eta_p^2=.65$ and a significant frequency effect, $F(5,225)=3.26$, $MSE=25.89$, $p<.01$, $\eta_p^2=.07$. The group x frequency interaction was also significant, $F(10,225)=209.61$, $MSE=25.89$, $p<..001$, $\eta_p^2=.26$. For all frequencies, the planned comparisons ($p<.05$) indicated that the young control participants differed significantly from the young participants with a reduced hearing level (at 250 Hz, $\eta_p^2=.32$; at 500 Hz, $\eta_p^2=.35$; at 1000 Hz, $\eta_p^2=.28$; at 2000 Hz, $\eta_p^2=.42$; at 3000 Hz, $\eta_p^2=.40$ and at 4000 Hz, $\eta_p^2=.23$) and from the elderly participants (at 250 Hz, $\eta_p^2=.15$; at 500 Hz, $\eta_p^2=.26$; at 1000 Hz, $\eta_p^2=.26$; at 2000 Hz, $\eta_p^2=.50$; at 3000 Hz, $\eta_p^2=.65$ and at 4000 Hz, $\eta_p^2=.58$). By contrast, the young participants with a reduced hearing level and the older participants were matched for the all frequencies up to 2000 Hz (at 250 Hz, η^2_p=.06; at 500 Hz, η^2_p=.02; at 1000 Hz, η^2_p=.001 and at 2000 Hz, η^2_p=.02) except for the highest frequencies of 3000 Hz, η^2_p=.23 and of 4000 Hz, η^2_p=.27. Figure 1 displays mean bilateral auditory thresholds as a function of participant group and tone frequency.

(Figure 1 about here)

Given that the frequencies necessary for phoneme perception are generally situated below 3000 Hz (Delattre, Liberman, & Cooper, 1955; Liberman, Delattre, & Cooper, 1952; Raphael, 2005), the two groups with reduced hearing level were matched for those frequencies which are the most involved in language comprehension and therefore also in processing of the auditory-verbal items used in the STM tasks.

Mean pure-tone audiometry thresholds (PTAs) for 500, 1000 and 2000 Hz were 17.13 dB HL (*SD*=4.61) and 17.24 dB HL (*SD*=6.27) for the old and the young hearing-matched participants respectively. This shows that the older and young adults with hearing loss showed relatively mild hearing impairment, given that clinical hearing loss is typically situated in the 25-30 dB HL range (McCoy et al., 2005). The group of older participants may be considered, to some extent, as a special group with relatively good hearing capacities in comparison to an average elderly population but the experimental approach of this study required the matching of young and older participants on hearing thresholds, leading to the selection of elderly participants with less severe hearing impairment. Importantly, the hearing levels of the elderly participants recruited in this study are comparable to those of the participants typically recruited in previous studies exploring and showing significant age effects on cognition, and hence it is particularly relevant to explore the role of this relatively mild hearing loss as a potential explanatory variable of the age effects observed in auditory-verbal cognitive tasks (e.g., Borella, Carretti, & De Beni, 2008; Peters, Majerus, De Baerdemaeker, Salmon, & Collette, 2009; Van der Linden et al., 1999).

None of the participants wore a hearing aid. Indeed, in this study, we aimed at analyzing the impact of reduced hearing level on STM performance in natural conditions, without any hearing improvement via hearing aids. A number of studies (e.g., Lunner, 2003, see also the discussion of Hoi Ning Ng, Rudner, Lunner, Syskind Pedersen, & Rönnberg, 2013) have suggested that correction of hearing loss with hearing aids improves cognitive performance. Moreover, Wingfield et al. (2006) discussed that two out of three elderly adults with hearing loss do not use hearing aids. We assumed that choosing participants without hearing aid would be more representative of the average elderly population. Finally, given that the participants' mean PTAs were within the normal range, the participants, especially the younger ones, did not feel the need to wear hearing aids because they were not conscious of having reduced hearing levels.

In order to rule out any differences in educational level, we retained, for all groups, only participants with undergraduate level of education and a total of 12 to 15 years of education.

The young participants with and without reduced hearing level further had to be matched for verbal knowledge and reasoning abilities. This was controlled via the French version of the Mill Hill synonym judgment test (Deltour, 1993). The ANOVA indicated a significant effect of group, $F(2,45)=5.51$, $MSE=.004$, $p<.01$, $\eta_p^2=.20$ and the planned comparisons ($p<.05$) showed no significant difference in verbal scores between the two young groups, $\eta_p^2=.001$. However, as could be expected, the comparisons ($p<.05$) also indicated that the elderly group showed higher verbal scores than the young control participants, $\eta_p^2=.15$, and the young participants with a reduced hearing level, $\eta_p^2=.16$ (e.g., Verhaeghen, 2003). All participants were native French speakers. Participants had normal or corrected-to-normal vision. No participant showed a history of neurological, neuropsychological, psychiatric disorders or medication use that could have impaired their performance. In elderly participants, we also controlled for senile dementia, by requiring all participants to show performance above the cut-off score of 130/144 on the Mattis Dementia Rating Scale (Schmidt, Freidl, Fasekas, Reinhart, & Grieshofer, 1994). Finally, cognitive processing speed was assessed via a speeded sound classification task for high- (2000 Hz) and low-pitched (500 Hz) tones. As expected, a significant group effect, $F(2,45)=3.88$, $MSE=.008$, $p<.05$, $\eta^2_p=.15$, was observed and the planned comparisons ($p<.05$) showed that the elderly participant group were slower than the young controls participants, $\eta^2_p=.12$, and from the young participants with a reduced hearing level, $\eta^2_p=.10$ (e.g., Salthouse, 1996). Demographic and statistical data are summarized in Table 1.

(Table 1 about here)

Materials

STM tasks.

Immediate serial recall of words.

A first task assessed immediate serial recall for auditorily presented word lists of increasing length. This task has been widely used in the STM literature. The task used here was adapted from Majerus and Van der Linden (2003) and was comprised of 84 high frequency words with a consonant-vowel-consonant (CVC) structure (>200 occurrences per million; Content, Mousty, & Radeau, 1990); the stimuli were presented in sequences ranging from 1 to 6 items, with 4 trials per sequence length. The sequences had been recorded by a female speaker in a sound attenuating room at the rate of one item per second, stored on computer disk, and were presented in ascending order via headphones connected to a PC. The headphones were circumaural headphones, attenuating ambient noise. The items were presented at a comfortable hearing level (70 dB SPL) frequently chosen in auditory verbal STM experiments (e.g., Majerus & D'Argembeau, 2011; Tun et al., 2009). At the end of each trial, the participants were asked to recall the words within their order of presentation. High frequency words were used in order not to disadvantage young participants who typically have lower vocabulary knowledge, especially for low frequency words, as compared to elderly participants. We computed the proportion of words recalled in correct serial position by pooling over trials and sequence lengths.

Immediate serial recall of phonologically similar and dissimilar words.

A second immediate serial recall task contrasted lists with phonologically similar and dissimilar words. The task was adapted from Majerus, Van der Linden, Poncelet, and Metz-Lutz (2004) and was comprised of 8 phonologically dissimilar and 8 phonologically similar words, randomly assigned to auditory sequences ranging from 2 to 8 items, presented in ascending order, with 4 trials per sequence length. The same 8 phonologically similar and dissimilar words were presented throughout the task. The phonologically similar words differed only by the onset phoneme (e.g., “roi”, “loi”, “bois”, meaning king, law, wood, respectively). All words were of moderate lexical frequency (from 30 to 75 occurrences per million; Baudot, 1992) and matched for imageability (Coltheart, 1981). Presentation and recall procedures were the same as for the other immediate serial recall task. We computed the proportion of words recalled in correct serial position as a function of phonological similarity condition, by pooling over trials and sequence lengths within each condition.
This task allowed us to study the presence of a phonological similarity effect that could affect the participants' performance in several ways. First, the words in the similar list condition may lead to greater within-list item confusions in the two hearing-impaired groups. Second,

the high phonological neighborhood of the items in the phonologically similar condition may increase within-list item confusions for all participants; partial phonological activation being sufficient to activate all items located in a dense phonological neighborhood.

Digit serial order reconstruction.

A final STM task was an adaptation of standard auditory digit span tasks, by focusing more specifically on the retention of serial order information, another critical component of auditory STM. This task consisted of the auditory presentation of digit sequences by increasing length (6 to 9 digits), with 6 trials per sequence length (Majerus, Poncelet, Van der Linden, & Weekes, 2008). Recording and presentation procedures of the stimuli were the same as for the preceding tasks. At the end of each trial, the participants were given cards on which the digits presented during the sequence were printed (cards were given in numerical order); participants had to sort the cards according to their order of presentation, by ordering them on the desk from left to right. The proportion of digits and positions correctly reconstructed was determined. In order to maximize serial order processing and to minimize item processing during retrieval, item information was given to the participants by providing cards with the digits presented in the lists, ensuring that only serial order information had to be reconstructed (e.g., Brock & Jarrold, 2005; Majerus, Leclercq et al., 2009; Majerus, Poncelet, Elsen, & Van der Linden, 2006; Majerus, Poncelet, Van der Linden, & Weekes, 2008).

Speeded nonword repetition.

A final task assessed participants' online phonological processing abilities in order to control for the impact of hearing status on identification and access to sublexical phonological information. This task consisted in the repetition of 20 single nonwords, each nonword being presented only once. The participants were asked to repeat each single nonword immediately after its presentation, which required a minimal STM load. In order to avoid lexical reconstruction, the nonwords were constructed to be distant from French phonological structures by selecting phoneme co-occurrences of low phonotactic frequency according to the phonetic database of French by Tubach and Boë (1990). All items had a bisyllabic CVC-CVC structure and had been prerecorded by a female speaker in a sound attenuating room. The items were presented via circumaural headphones connected to a PC and presented at 70 dB SPL. We determined the proportion of items correctly recalled.

Procedure

Participants were tested individually in a quiet room in a single session. The different tasks were administered in random order.

Results

For word ISR, the ANOVA showed a significant difference between the three groups, $F(2,45)=5.60$, $MSE=.01$, $p<.01$, $\eta^2_p=.20$. Planned comparisons ($p<.05$) indicated that the young control participants performed higher than the young participants with a reduced hearing level, $\eta^2_p=.09$, and the elderly participants, $\eta^2_p=.19$, which did not differ from each other, $\eta^2_p=.03$. Figure 2 presents the results for each group (controls, young hearing-matched and older participants) on the word immediate serial recall (ISR) task.

(Figure 2 about here)

On ISR for phonologically similar and dissimilar word lists, we performed a mixed ANOVA with 3 (group: young adult controls, young adults with a reduced hearing level, older adults) x 2 (list: similar word list, dissimilar word list) cells. The analyses revealed a significant group effect, $F(2,45)=8.42$, $MSE=.02$, $p<.001$, $\eta^2_p=.27$ (see Figure 3). For the similar word list condition, planned comparisons ($p<.05$) indicated that the control participants showed higher performance than the young adult participants with a reduced hearing level, $\eta^2_p=.15$, and the elderly participants, $\eta^2_p=.18$, but that there was no significant difference between the young adults with reduced hearing level and the older participants, $\eta^2_p=.002$. Similarly, for the dissimilar condition, planned comparisons ($p<.05$) indicated that the young participants with reduced hearing level and the elderly participants did not significantly differ from each other, $\eta^2_p=.06$, and both performed at lower levels than the adult control participants (young participants with a reduced hearing level vs. controls, $\eta^2_p=.11$; elderly participants vs. controls, $\eta^2_p=.26$). The list effect was also significant, $F(1,45)=18.95$, $MSE=.004$, $p<.001$, $\eta^2_p=.30$, performing being better in the dissimilar condition than in the similar condition all groups confounded. The group x list interaction was not significant, $F(2,45)=1.30$, *ns*. Although we initially predicted that participants with a reduced hearing level may be more affected by phonologically similar items, the results showed that the phonological similarity effect was the same for the three groups, but that reduced hearing status led to poorer performance for both stimulus conditions. These results may be explained by several factors. First, the absence of an interaction could be related to the dense phonological neighborhood of items in the phonologically similar condition that may have facilitated activation of both target items and phonologically similar items, and this even for initial partial phonological activations, leading to similar effects in both normal hearing participants and participants with reduced hearing levels. Second, the fact that we used closed lists of items for both the similar and the dissimilar conditions, may have led to enhanced stimulus confusability in terms of between-list intrusions in both similar and dissimilar conditions, and this for all groups.

(Figure 3 about here)

On the digit serial order reconstruction task, the ANOVA revealed a significant difference between the three groups, $F(2,45)=7.55$, $MSE=.005$, $p<.001$; $\eta_p^2=.25$ (see Figure 4). Planned comparisons ($p<.05$) again indicated that the control participants performed higher than the young adult participants with a reduced hearing level, $\eta_p^2=.17$, and the elderly participants, $\eta_p^2=.22$, which did not differ from each other, $\eta_p^2=.006$.

(Figure 4 about here)

Finally, on the speeded nonword repetition task[1], assessing the impact of hearing status on perceptual and phonological identification outside a STM context, the ANOVA did not show any significant group effect, $F(2,45)=.43$, *ns* (see Figure 5).

(Figure 5 about here)

[1] For the pure-tone audiometry and the speeded nonword repetition tasks, the assumption of normality was not met for score distributions. Therefore, the analyses were also run using nonparametric Kruskal Wallis tests, leading to an identical outcome of results.

Discussion

Although verbal STM is most frequently measured using auditory presentation of memoranda and that a majority of the elderly population have some mild auditory loss (Surprenant, 2007), very few studies have considered the importance of auditory status on auditory STM performance in aging. Previous studies indirectly showed that age-related performance decrement in auditory-verbal STM tasks can be at least partially accounted for by hearing status, via statistical control of hearing levels or experimental control of the audibility of memoranda by lowering the level of the presentation of the items or by adding a background noise during the presentation of the items (Baldwin & Ash, 2011; Cervera et al., 2009; Murphy et al., 2000; Pichora-Fuller et al., 1995; van Boxtel et al., 2000). In the present study, we performed a direct and simple test of the impact of reduced hearing level on STM performance, by comparing STM capacities of elderly participants with a reduced hearing level to young adult participants, matched for hearing threshold on the frequencies relevant for speech processing. Moreover, this matching procedure allowed us to directly test the importance of hearing loss as an explanatory factor of age-related STM decline in ‘natural’ conditions, i.e., without using any sound amplification. Indeed, given that the aim of our study was precisely to explore the impact of reduced hearing levels on auditory-verbal STM performance, it would have been counterproductive in this study to increase hearing levels in the hearing-reduced participants. More generally, a number of studies have already shown that such amplifications improved participants’ STM performance (e.g., Baldwin & Ash, 2011; Heinrich & Schneider, 2011; Lunner, 2003).

We observed that elderly participants and hearing-matched young participants showed equal levels of performance in all verbal STM tasks, and performed overall lower than the normal-hearing young control participants. These results suggest that reduced hearing levels are an important explanatory factor of reduced STM performance, and account for a significant part of age-related difficulties in STM performance, at least for passive auditory immediate serial recall tasks as used in the present study. These findings are critical when interpreting age-related effects on verbal STM performance. Indeed, elderly participants may show lower STM performance which is often interpreted as being due to age-related cognitive decline while an important part of this lower performance is actually due to reduced auditory capacities. Moreover, the mean PTAs of the young and older participants with reduced hearing level indicate that their hearing difficulties fall within the normal range. Thus, the present results show that even a relatively mild reduction of hearing thresholds still outside the pathological range already leads to lower STM performance. This statement is especially noteworthy for the older participants recruited in the present study. Indeed, most of past studies exploring age effects on auditory-verbal STM performance controlled for hearing status by excluding participants with pathological hearing thresholds (> 25 dB HL), but these studies are likely to have included elderly participants with more mildly reduced hearing thresholds as the participants recruited for the present study (e.g., Borella et al., 2008; Peters et al., 2009; Van der Linden et al., 1999). This means that the age effects observed on auditory-verbal STM performance in previous studies may in fact be related to subtle hearing impairment, as suggested by the result of the present study. Indeed, in this study, the differences on STM tasks between our subtly hearing-impaired older participants and the young hearing-matched participants were rather minimal.

The present data do not allow us to define the underlying mechanisms that explain this direct impact of hearing status on auditory-verbal STM performance and further studies are needed to explore these mechanisms. The results, however, allow us to advance some hypotheses. Firstly, because the young participants with hearing difficulties displayed the same level of STM performance as the elderly participants, the hypothesis of an age-related neural degeneration is not supported by the present data (Baltes & Lindenberger, 1997;

Humes & Floyd, 2005; Lindenberger & Baltes, 1994): age-related neural degeneration obviously cannot be invoked to explain the poorer STM performance in our young hearing-matched participants. A second possibility is that reduced hearing levels lead to poorer perception and to impoverished perceptual representations of items during presentation, resulting in inaccurate and noisy encoding of representations in STM (Lindenberger & Baltes, 1994; Murphy et al., 2000). At the same time, we controlled for this possibility by administering a speeded nonword repetition task with minimal STM load: the identical performance levels for the three groups on this task indicate that reduced hearing levels in the hearing-reduced participant groups were not sufficiently severe to lead to misperceptions of target stimuli. This is also in line with a number of studies showing that individuals with hearing impairment may present decreased auditory-verbal STM performance while being able to correctly perceive auditory-verbal information (McCoy et al., 2005; Pichora-Fuller, 2003; Pichora-Fuller et al., 1995; Rabbit, 1968, 1991; Wingfield, Tun, & McCoy, 2005).

An alternative hypothesis has been proposed, considering that mildly impaired hearing levels do not prevent accurate encoding of auditory information in most cases, but require higher attentional efforts to achieve perceptual success (Mac Coy et al., 2005; Piquado, Cousins, Wingfield, & Miller, 2010; Rabbit, 1968, 1991; Wingfield et al., 2005). This is particularly likely in the case of the present study, where participants showed mildly reduced, but not pathological hearing thresholds. This greater involvement of attentional processes during auditory decoding will have a direct impact on auditory-verbal STM performance, since attentional processes define the bottleneck of STM performance. Many studies have shown that controlled and selective attention are critical determinants of STM performance, and recent theoretical models of STM consider that attention is needed to maintain items in an activated state until recall (Cowan, 1995; Majerus & D’Argembeau, 2011; Oberauer, 2002). It has been shown that this is not only the case for complex storage-and-processing memory tasks (typically referred to as working memory tasks) but also for more ‘passive’ STM tasks, such as the immediate serial recall tasks used in the present study (Majerus et al., 2012; Majerus, Heiligenstein, Gautherot, Poncelet, & Van der Linden, 2009). Therefore, if attentional resources are already allocated to auditory decoding of input information, then less attentional resources will be available for STM encoding and maintenance, leading to lower STM performance in individuals with a reduced hearing level, whether old or young.

We should note here some limitations in the methods of the speeded nonword repetition task. The fact that both groups with reduced hearing levels did not differ from the young normal hearing control group on the speeded nonword repetition task indicates that the three groups were able to correctly repeat phonologically complex information and led us to assume that the items were well perceived by all participants. However, we cannot dismiss the possibility that the nonwords may nevertheless have been more effortful to identify and process in the groups with reduced hearing levels (Tun, Benichov, & Wingfield, 2010). An analysis of response latencies would have been informative here since the hypothesis of a greater recruitment of attentional resources during auditory decoding predicts a slowing of auditory decoding during nonword processing. Although this slowing would have been difficult to interpret in the elderly group, due to more generalized cognitive slowing and slowed articulation speed (e.g., Maylor et al., 2009; Salthouse, 1996), it would have been interesting to observe slowed nonword repetition performance also in the young group with reduced hearing levels.

Finally, the present study does not imply that there are no hearing-independent age effects on STM performance at all. When using passive STM tasks in hearing-matched participant groups, we show in the present study that age effects disappear. It is however likely that these effects re-appear if using STM/working memory tasks with higher executive processing load since executive processes are known to be impaired more generally in elderly people (e.g., Brink & McDowd, 1999; Gaeta et al., 2001; Kane et al., 1997; Milham et al., 2002). In line with this assumption, Tun et al. (2009) observed independent age and hearing status effects on immediate memory tasks with both storage and processing components.

To conclude, the present study shows that hearing status is an important determining factor of auditory-verbal STM performance, accounting for a significant part of the age differences commonly observed in standard auditory-verbal STM tasks, and this even if the reduced hearing levels of the participants still fall within a normal range.

Acknowledgements

This research was supported by the Belgian Fund for Scientific Research (F.R.S.-FNRS) and the University of Liège.

We would like to thank Amandine Vallier and Mylène Bourgeois for their contribution in data collection.

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Table 1

Demographic data and hearing thresholds (mean and standard deviations) of the three groups

Variable	Young control group	Young hearing-matched group	Elderly group
Number of participants	16	16	16
Mean age (years)	23.31 (1.25)	24.87 (2.66)	69.66 (5.64)
Gender (M/F)	6/10	5/11	5/11
Pure-tone Thresholds (dB HL)[a]			
250 Hz	9.53 (4.21)	19.84 (8.92)	15.94 (4.73)
500 Hz	8.91 (2.58)	18.91 (7.41)	17.03 (6.21)
1000 Hz	7.66 (3.70)	16.09 (7.24)	15.78 (5.75)
2000 Hz	5.47 (5.18)	16.72 (6.04)	18.59 (5.40)
3000 Hz	5.16 (3.47)	16.25 (6.95)	23.75 (6.12)
4000 Hz	5.94 (7.18)	16.56 (7.63)	28.28 (9.30)
Mill Hill (Z-scores)	- 0.28 (1.00)	- 0.34 (0.74)	0.62 (0.99)
Processing speed (ms)	395.64 (80.18)	398.47 (62.14)	475.41 (110.94)

[a] Bilateral mean pure-tone audiometry thresholds

Figure captions

Figure 1

Both ears' mean pure-tone audiometry thresholds at 250, 500, 1000, 2000, 3000 and 4000 Hz of the young control group (controls), the young hearing-matched group (young hearing-matched) and the elderly group (elderly)

Figure 2

Performance on the ISR of words in the young control group (controls), the young hearing-matched group (young hearing-matched) and in the elderly group (elderly)

Figure 3

Performance on the in the young control group (controls), the young hearing-matched group (young hearing-matched) and in the elderly group (elderly)

Figure 4

Performance on the serial order reconstruction task in the young control group (controls), the young hearing-matched group (young hearing-matched) and in the elderly group (elderly)

Figure 5

Performance on the speeded nonword repetition task in the young control group (controls), the young hearing-matched group (young hearing-matched) and in the elderly group (elderly)

Figure 1

Both ears' mean pure tone audiometry thresholds at 250, 500, 1000, 2000, 3000 and 4000 Hz of the young control group (controls), the young hearing-matched group (young hearing-matched) and the elderly group (elderly)

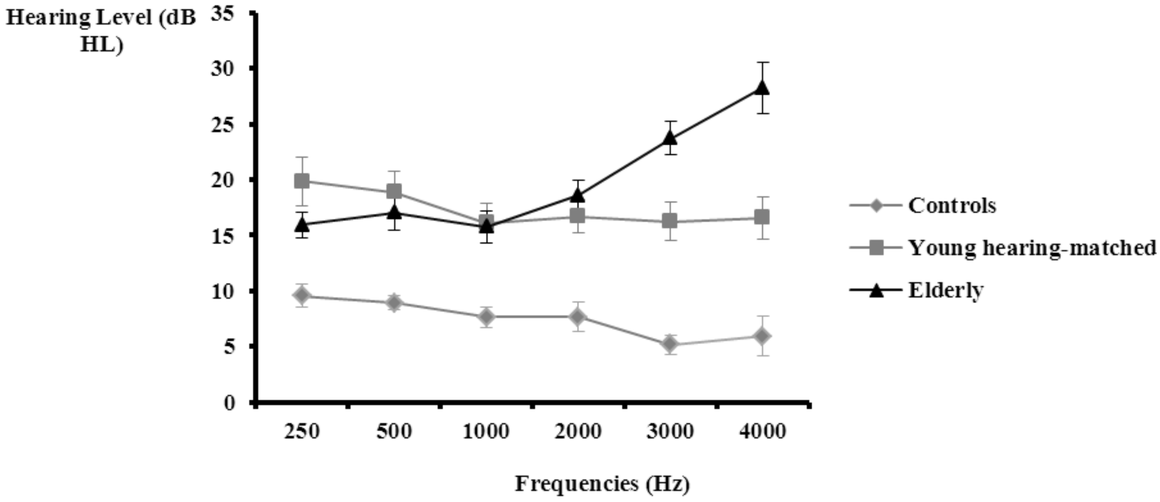

Figure 2

Performance on the ISR of words in the young control group (controls), the young hearing-matched group (young hearing-matched) and in the elderly group (elderly)

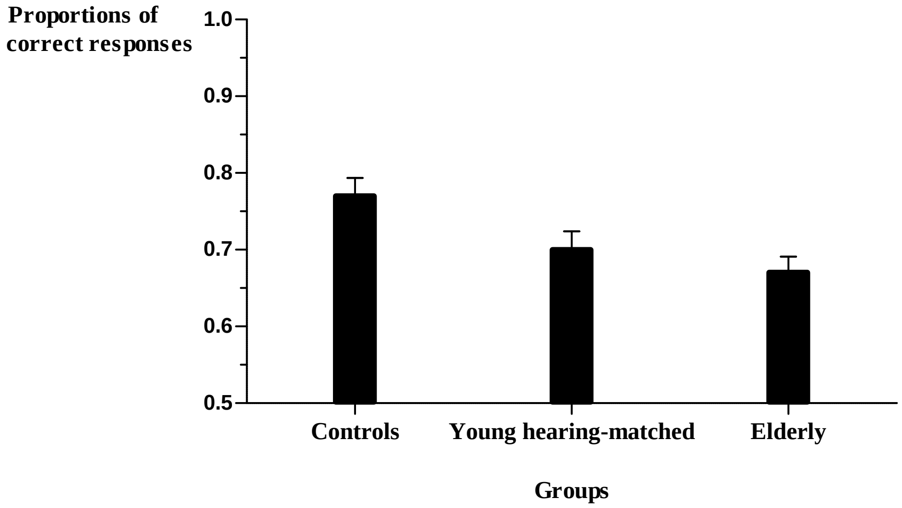

Figure 3

Performance on the and ISR of phonologically similar and dissimilar words in the young control group (controls), the young hearing-matched group (young hearing-matched) and in the elderly group (elderly)

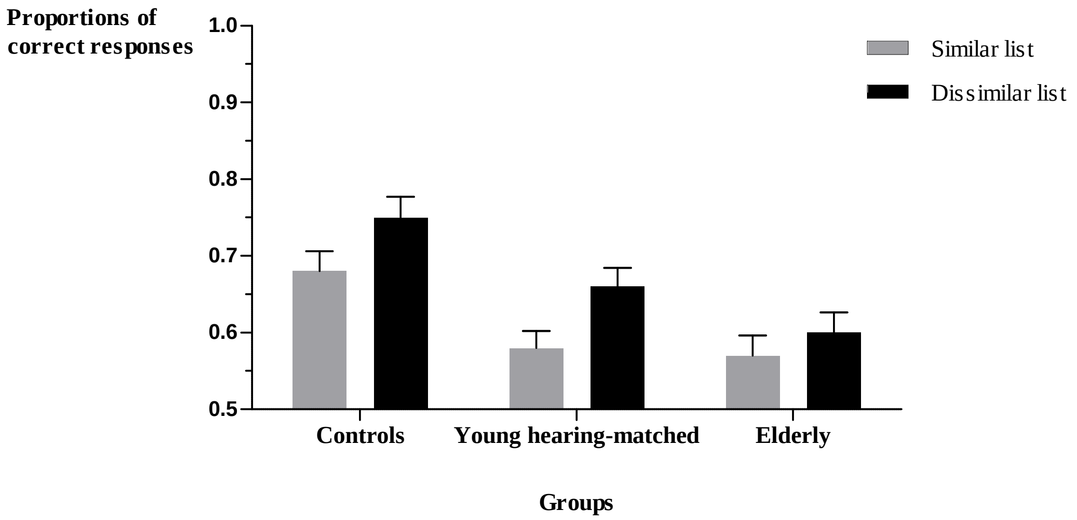

Figure 4

Performance on the serial order reconstruction task in the young control group (controls), the young hearing-matched group (young hearing-matched) and in the elderly group (elderly)

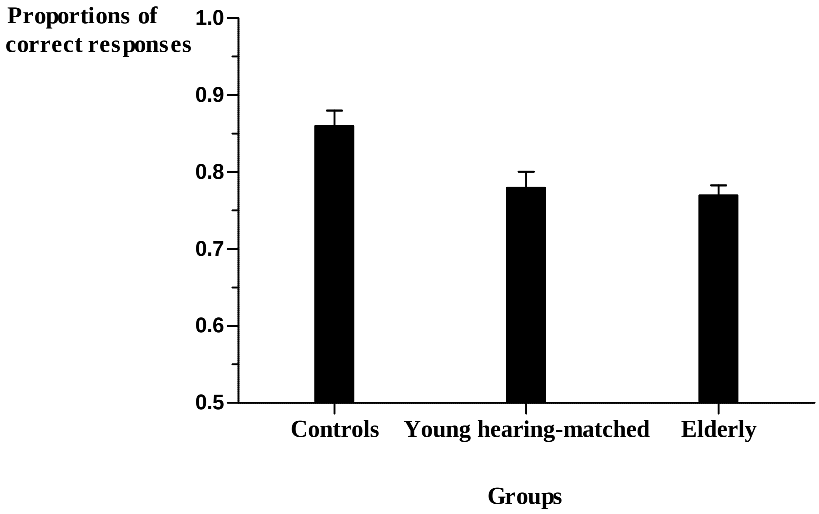

Figure 5

Performance on the speeded nonword repetition task in the young control group (controls), the young hearing-matched group (young hearing-matched) and in the elderly group (elderly)