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Plasticity After Hearing Rehabilitation in the Aging Brain

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Abstract

Age-related hearing loss, presbycusis, is an unavoidable sensory degradation, often associated with the progressive decline of cognitive and social functions, and dementia. It is generally considered a natural consequence of the inner-ear deterioration. However, presbycusis arguably conflates a wide array of peripheral and central impairments. Although hearing rehabilitation maintains the integrity and activity of auditory networks and can prevent or revert maladaptive plasticity, the extent of such neural plastic changes in the aging brain is poorly appreciated. By reanalyzing a large-scale dataset of more than 2200 cochlear implant users (CI) and assessing the improvement in speech perception from 6 to 24 months of use, we show that, although rehabilitation improves speech understanding on average, age at implantation only minimally affects speech scores at 6 months but has a pejorative effect at 24 months post implantation. Furthermore, older subjects (>67 years old) were significantly more likely to degrade their performances after 2 years of CI use than the younger patients for each year increase in age. Secondary analysis reveals three possible plasticity trajectories after auditory rehabilitation to account for these disparities: Awakening, reversal of deafness-specific changes; Counteracting, stabilization of additional cognitive impairments; or Decline, independent pejorative processes that hearing rehabilitation cannot prevent. The role of complementary behavioral interventions needs to be considered to potentiate the (re)activation of auditory brain networks.

Keywords

auditory loss, presbycusis, cochlear implant, aging, cognitive decline

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Introduction

Age-related hearing loss, presbycusis, causes a considerable socioeconomic burden in industrialized societies due to its increasing prevalence in the growing aging population (Livingston et al., 2020). It afflicts one out of three persons by age 65, one out of two by age 75, and up to 81% in those over 80 years (Goman & Lin, 2016; Sharma et al., 2020). Presbycusis involves the loss of sensory cells in the cochlea, stria vascularis impairment, and the degeneration of auditory neurons, resulting in a typically sloping pure tone audiometric profile (Keithley, 2020), in which high-frequency sounds become more difficult to hear than low. It may consequently be seen as a periphery-restricted pathological process that indirectly affects central functioning by enhancing cognitive burden (Füllgrabe & Rosen, 2016), social isolation, and cognitive decline (Davis et al., 2016; Lee et al., 2018; Pichora-Fuller et al., 2016). Thus, epidemiologic studies have demonstrated a statistical association between presbycusis and dementia (Armstrong et al., 2020; Gurgel et al., 2014; Lin et al., 2013). Although the causal links and interactions between these conditions remain insufficiently understood (Deal et al., 2017; Gallacher et al., 2012; Lin, Metter, et al., 2011; Loughrey et al., 2018), this association suggests that auditory rehabilitation and auditory interventions could jointly contribute to promoting the awakening or at least the maintenance of the cognitively declining brain (Amieva et al., 2015; Brewster et al., 2020).

Indeed, although positive—on average—in the aging population, individual effects are surprisingly variable; some patients do not optimally benefit from these technologies and eventually abandon them (Moberly, Bates, et al., 2016). Many factors arguably interact to generate the

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apparent heterogeneity in rehabilitation outcomes. They include compliance and satisfaction in hearing devices (Solheim et al., 2018; Solheim & Hickson, 2017), limited progression of performance in critical functions such as auditory attention, speech processing, and comprehension, especially in noisy environments (Moberly, Houston, et al., 2016; Nittrouer et al., 2016). It is, therefore, essential to better characterize this heterogeneity in the population to understand how central processing factors and rehabilitation interact.

The medical and scientific community generally acknowledges the benefits of cochlear implantation in the older population regarding absolute improvements in oral communication and quality of life (Knopke et al., 2016). However, disagreements exist regarding the relative performance gain of this population when compared to younger recipients. Although some authors observed lower performance in quiet (Friedland et al., 2010; Holden et al., 2013), and in noise (Giourgas et al., 2021), others have found such effects only in noise (Lenarz et al., 2012) or no difference regardless of the conditions (Carlson et al., 2010; Hast et al., 2015). These discrepancies may pertain to the limited number of subjects tested ($n < 100$ for most of them, except for Giourgas et al. (2021) where $n = 446$). Based on retrospective information from 2251 cochlear implantees and accounting for the relative influence of 15 clinical factors, Blamey et al. (2013, 2015) and Lazard, Vincent, et al. (2012) showed a significant negative effect of age from 70 years onward at the time of cochlear implantation on speech outcomes. As the learning curve after cochlear implantation has been attributed in part to plasticity (McKay, 2018), we sought to investigate in more details whether older subjects can rely on comparable plasticity (learning curve) as the younger population. Here, we explore the relevance of central processes—in particular neural plasticity—in an aging population, as a critical factor to account for these disparities, by reanalyzing the large dataset based on clinical predictors and outcomes of 2251 cochlear-implant recipients aged from 17 to 93 years, mentioned earlier (Blamey et al., 2013, 2015; Lazard, Vincent, et al., 2012). By comparing speech scores before implantation and their evolution with the implant between two timepoints (6 months and 2 years) among this sample, we identified a cutoff around age 70 at which performance does not increase in the same proportions as the rest of the population, or even degrades. We describe multiple trajectories and relate them to different profiles of plasticity after auditory rewiring and further discuss these results in the light of healthy and pathological cognitive aging.

Material and Methods

Dataset

This reanalysis used data from the multicentric study published by Blamey et al. (2013, 2015) and Lazard, Vincent, et al. (2012), in agreement with the statement that the authors accepted to share the data upon request for academic, non-commercial purposes (Lazard, Vincent, et al., 2012). The dataset consisted of retrospective information for 2251 cochlear implant (CI) recipients implanted between 2003 and 2011 and evaluated with speech tests in quiet. This project was approved by the Royal Victorian Eye and Ear Hospital Human Research Ethics Committee (Project 10/977H, Multicentre Study Of Cochlear Implant Performance In Adults).

Speech scores in quiet before implantation and in best-aided condition, and at two postoperative timepoints were requested from the clinics for each recipient. The early postoperative score was collected 6 months after the surgery (T1), and the late postoperative score was collected after 2 years of use (T2), on average. We calculated percentile ranking from the speech test scores for each patient within each center, but separately for the preoperative and postoperative scores. Percentile ranking allows normalizing data for tests conducted in different languages and presented at different intensity levels across the centers. All patients from each center were tested with the same speech material and under the same conditions. Using ranking thus removes differences in clinical practice without removing the relative differences between patients within a specific clinic, with the distribution of the scores varying uniformly from 0 to 100. Percentile ranking was first performed within each clinic, followed by the subsequent gathering of the ranked scores.

Patients' Selection

The statistical analysis was performed on the entire group aged from 17 to 93 years. All subjects were unilaterally implanted and benefited from speech therapy after implantation. Observance of speech therapy was an inclusion criterion at the time of data collection. Although the duration and type of intervention are not known in detail (this specific information was not requested during data collection and is no longer accessible), the practice was the same within each clinic. As mentioned, Blamey and Lazard showed a significant negative effect of age on speech outcomes from 70 years at cochlear implantation. We used this 70-year cutoff at implantation to define a boundary in the population and to compare an "Older" ($n = 699$) and a "Younger" Group ($n = 2067$). This allowed us to test for interactions investigating how the relationship between speech listening improvement (learning) and age changes over the course of the life span.

Statistical Analyses

A linear mixed effect model was developed using the statsmodels package (Seabold & Perktold, 2010) in Python (version 3.10) to assess the relationship between speech improvement and age while controlling for several other factors. The model was fit to predict the dependent variable, participant's postoperative score (score), using a nested

repeated measure model using Etiology as the first level and Patient ID as the second level repeated measure. The model used several features to predict the score variable including: Session (T1 & T2), Age at cochlear implantation (ageCI), estimated duration of severe hearing loss (durSevHL), the participants' preoperative score in best-aided condition in quiet (preopScore) and the interactions of these three preceding variables with Session. Although significant coefficients for any of the main terms show a relationship between that feature and participants' overall score, the interactions display evidence for learning, how participants improve from one session to the next. In addition to these terms, we included one three-way interaction between Age Group, Session, and AgeCI to investigate the effect of age and learning changes in the older population. The resulting model was fit, and parameters were tested for significance using a standard z test.

The three-way interaction was further investigated by *post hoc* analysis of the residuals, controlling for unrelated significant features. For each age group and session, a line was fit between age and the resulting score. The slopes were compared within each session and the significance test was assessed using a Z-test using the variance of the model fit as in the below equation:

$$Z = \frac{\mu_{old} - \mu_{young}}{\sqrt{(\sigma^2_{old} + \sigma^2_{young})}}$$

where μ_{grp} represents the estimated slope of the old or young group and σ^2_{grp} is the variance of that parameter estimate.

Although the age boundary of 70 was subjectively established from previous literature (Blamey et al., 2013), it was unclear how much these results were reliant on this boundary choice or if the three-way interaction found was based on the nature of the features set. As such, we re-ran the analysis repeatedly changing the age boundary and investigating how Z statistic for the three-way interaction changed. We chose age boundaries from 18 to 92 in one-year increments and extracted the Z-statistic for the three-way interaction.

Extracting Profiles of Behavior

We investigated whether the effects of age shown above are consistent across participants or if different underlying clinical profiles exist that may drive this effect. To do so, we modeled the distribution of score differences across sessions as a mixture of one to three Gaussian distributions:

$$p_\Delta(x) = \sum_{i=1}^{I} (w_i \cdot \mathcal{N}(x|\mu_i, \sigma_i^2))$$

where

$$1 = \sum_{i=1}^{I} w_i$$

where I is equal to 1, 2, or 3.

Models were fit through optimization; minimizing the negative log-likelihood of the above equation given the data using the minimize function of SciPy (version 1.7.3). Model fits were then compared using the Akaike Information Criterion (AIC), (Akaike, 1974). Model fitting across the whole population found two distributions to be the best fit, one highly stable population that slightly increases performance and one highly variable population showing both high increases in the improvement and large decreases as well. We split this population into three categories (variable improvement, stable and variable decline) and compared the distribution of young and older populations in these categories using a chi-square test. After finding a significant difference, we then performed *post hoc* chi-square tests comparing each category against the summation of the other two. We also assessed the Gaussian Mixture model fits in both the Older and Younger groups separately and compared the resulting means and number.

Results

To assess the importance of age on participant's improvement in speech comprehension scores in quiet, we developed a linear mixed effect model to predict participant scores from an array of features to control for other potentially correlated variables. In total, we considered age at cochlear implantation (ageCI), duration of severe hearing loss (durSevHL), and preoperative speech test scores (preopScore). In addition to these patient-specific features, we included session (first or second postoperative test) as well as the interaction of session with each of these terms. Although main terms reveal how each feature contributes to a patient's overall score, the interactions will show how each feature contributes to participants' improvement over time. Furthermore, we included one three-way interaction between ageCI, Session, and Age Group (older or younger) on the hypothesis that the relationship between ageCI and Session is not linear throughout the life span but instead steepens after a certain age (Blamey et al., 2013). Table 1 reveals the parameter fits and significance of each feature. Although all main terms had a significant effect on the overall score, only ageCI showed a significant interaction with the session. Furthermore, the three-way interaction was also significant ($p < .001$), potentially confirming our hypothesis of a steep drop-off of learning in older populations. Table 2 reveals parameter fits when insignificant parameters are removed, confirming the models stability.

To investigate further the nature of this interaction, we subtracted the predictions of the model related to the other features from the real data, yielding components related to ageCI and Session as well as the residuals, and then used ordinary least squares to fit a line for of how score is affected by age in each session and in each age group. The result is shown in Figure 1(a). Our estimate shows a significant difference in slope between older and younger population for the

Table 1. Coefficients of Linear Mixed Effects Model Explaining Participant Postoperative Performance from All Relevant Features.

Feature	Data type	Coefficient	Standard error	Z-statistic	*p* value
Intercept	N/A	40.070	3.349	11.964	<0.001
Session	Categorical	30.431	3.306	9.206	<0.001
ageCI	Continuous	−0.096	0.044	−2.169	0.031
durSevHL	Continuous	−0.217	0.07	−3.118	0.002
preopScore	Continuous	0.127	0.025	5.11	<0.001
Session:ageCI	Categorical : Continuous	−0.205	0.044	−4.680	<0.001
ageGroup:Session:ageCI	Categorical : Categorical : Continuous	0.106	0.030	3.572	<0.001
Session:durSevHL	Categorical : Continuous	−0.127	0.069	−1.851	0.064
Session:preopScore	Categorical : Continuous	0.024	0.025	9.63	0.336
Etiology Var	Categorical	0.117			
Subject Var	Categorical	410.251			

Table 2. Coefficients of Linear Mixed Effects Models Restricted only to Significant Features Predicting Participant Postoperative Performance from Relevant Features.

Feature	Data type	Coefficient	Standard error	Z-statistic	*p* value
Intercept	N/A	39.619	3.356	11.805	<0.001
Session	Categorical	31.531	3.029	10.411	<0.001
ageCI	Continuous	−0.091	0.045	−2.016	0.044
durSevHL	Continuous	−0.274	0.043	−5.114	<0.001
preopScore	Continuous	0.137	0.023	6.026	<0.001
Session:ageCI	Categorical : Continuous	−0.221	0.043	−5.114	<0.001
ageGroup:Session:ageCI	Categorical : Categorical : Continuous	0.106	0.030	3.585	<0.001
Etiology Var	Categorical	1.163			
Subject Var	Categorical	412.27			

second session ($Z = -2.4$, $p = 0.016$) but not for the first session ($Z = -1.6$, $p = 0.10$).

Although we have set the age boundary for the group distinction based on previous data (Blamey et al., 2013), it is reasonable to ask how this choice affected our results and whether the effect is specific to this boundary. For this reason, we ran the model repeatedly using all possible age boundaries and extracted the Z statistic of the three-way interaction. Figure 1(b) shows that the model only finds a significant value for this interaction with boundaries from 66 to 80 years of age with a peak value at 67, thereby objectively validating the initial choice of the cutoff value at age 70.

Although age shows a clear effect on learning, a sizable amount of variance remains unexplained, an effect that might be attributed to the emergence of distinct profiles—qualitatively intuitable from non-monotonic distributions in Figure 2(a) *left*—within the sampled population. To better understand the nature of this variance, we sought to breakdown our large sample into clinical profiles. By modeling the distribution of difference scores between T2 and T1 as a mixture of 1, 2, or 3 Gaussians, we found that the model fit best using two Gaussian distributions. A higher variance distribution (μ_1: 23.2, σ_1: 24.54, w_1: 0.86, see blue fit in Figure 2(a) *right*) and a more stable distribution (μ_2: 7.85, σ_2: 3.82, w_2: 0.14, see pink fit in Figure 2(a) *right*). These distributions create three regimes of profiles: two regimes dominated by the variant distribution with large increases and decreases in performance, and a stable population that consistently improves by a small amount.

From these regimes of datapoints (Figure 2(a)), we defined three different trajectories of speech outcomes: a gain in speech understanding (>15%), a stable outcome (0–15%), and a decrease in speech understanding (<0%). Their respective proportions are indicated in Figure 2(b) *top*. A Chi-square test comparing the respective distributions between the two groups within the three evolution profiles was performed ($\chi^2(2) = 60.17$, $p < .001$, Figure 2(b) *bottom*). In the Older group, there were fewer subjects than expected in the "gain" trajectory ($\chi^2(1) = 52.30$, $p < .001$), and more subjects than expected in the "decrease" trajectory ($\chi^2(1) = 31.69$, $p < .001$). However, the stable trajectory showed no change in subject concentration ($\chi^2(1) = 1.19$, $p = 0.27$). We consequently propose three distinct cognitive trajectories after implantation: Awakening, Stabilization/Counteracting, and Decline, suggesting different levels of plasticity in the older population.

A pattern where we find changes in the edge regimes but not in the middle could potentially be expected when comparing one distribution that is slightly lower than the other. Therefore, we fit the Gaussian mixture models to each age group to see how the underlying distributions change in each case. Figure 2(c) *left* shows that the Younger group

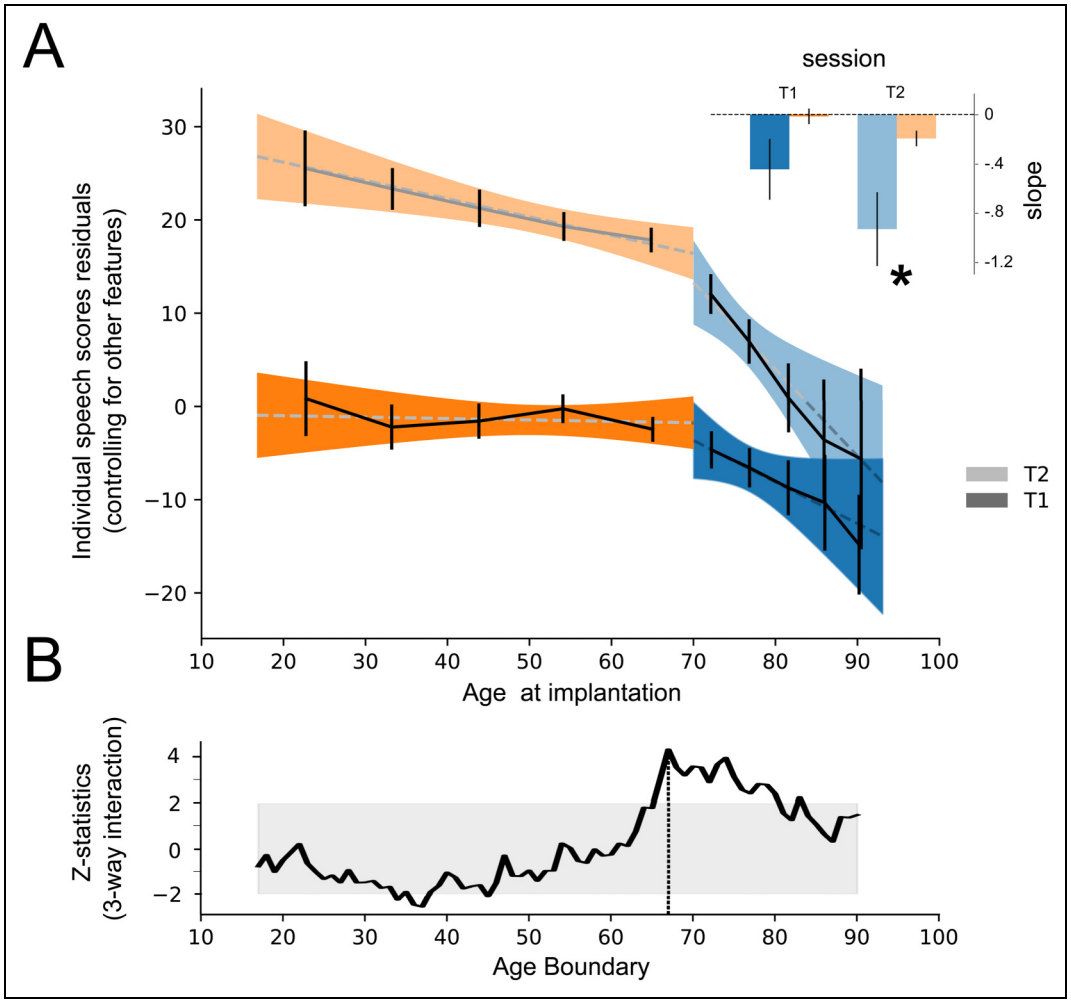

Figure 1. (a) Residual Speech Scores 6 (T1, Darker) and 24 (T2, Lighter) Months After Cochlear Implantation for Younger (Orange; <70) and Older (Blue; >70) Populations, as a Function of Age. Solid lines indicate binned averages ± SEM. Dashed lines and colored patch indicate ordinary least squares linear fit. Upper right inset shows slope parameter of linear fits (* indicates $p < .05$). These results demonstrate, in two large groups controlled for preoperative scores, duration of deafness, and etiology, that improvement in speech recognition following implantation is lower and reduces more quickly with age in subjects aged 70 years and more. (b) Strength of three-way interaction over potential age boundaries to determine the optimal cutoff value between younger and older populations. Light gray patch indicates threshold for significance ($p < .05$); dashed line indicates best cutoff value (67 years old).

yields a fit largely consistent with the whole population (μ_1: 26.77, σ_1: 25.11, w_1: 0.82; μ_2: 9.16, σ_2: 4.76, w_2: 0.18). The older group on the other hand yields a different outcome, now better fit by three Gaussians (μ_1: 18.42, σ_1: 22.34, w_1: 0.83; μ_2: 6.30, σ_2: 2.12, w_2: 0.11; μ_3: −6.81, σ_3: 3.50, w_3: 0.06, Figure 2(c) *right*). Although the stable (pink) peak 2 remains consistently in the 0–15% regime, the first distribution has a markedly lower mean reflecting the reduced numbers in the Older Group in the Awakening profile, with an increase in the Decline group enough to reveal a third (red) peak in the distribution (see Figure 2(c) *right*). Our results are, therefore, not consistent with a mean shift in the total population but rather reflect a stable population which persists into old age and a more plastic, more variable group that is much more age dependent.

Discussion

Altogether, our large-scale observations intimate that subjects rehabilitated by a CI are more susceptible to not fully restoring auditory function as a result of increased age. Furthermore, after age 67, this effect of rehabilitation drops off more precipitously with each increasing year. From 6 months to 2 years, this group's gain was significantly decreased over time, and their distribution showed that in 23% of cases, their performance even declined (*vs.* 11% in the younger group, Figure 2). We suggest that three distinct trajectories, potentially reflecting plasticity, may account for disparities in performance after hearing rehabilitation, the latter being insufficient to counteract cognitive decline in some cases. In line with another recent empirical observation

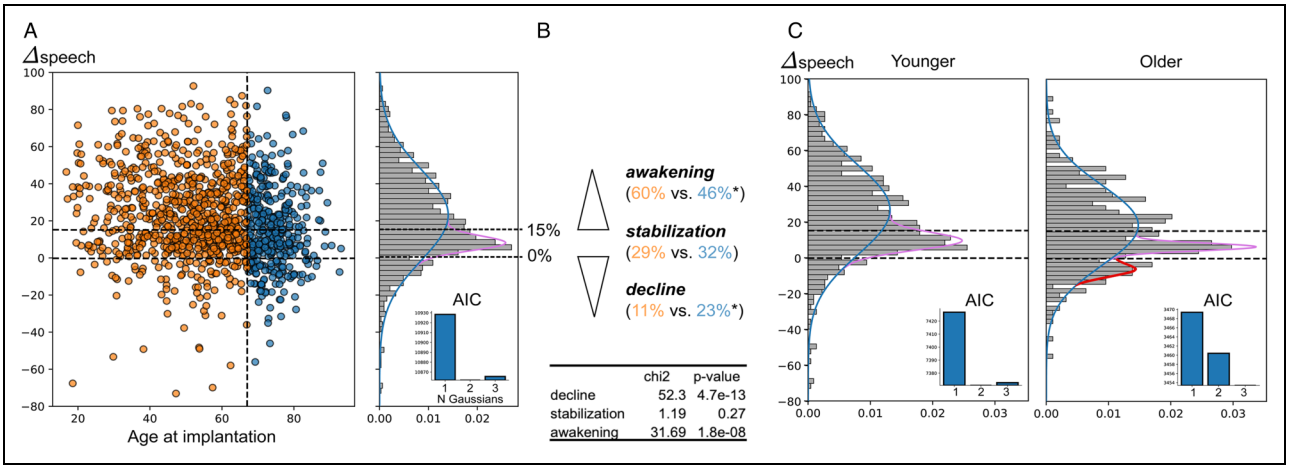

Figure 2. (a) *Left*, Speech Score Improvement (Δspeech = T2–T1) as a Function of Age at Cochlear Implantation. Subjects are grouped and color-coded according to the cutoff age (67 years old; vertical dashed line). Younger population in orange, older in blue. *Right*, histogram of speech scores improvement is best fit by two mixed Gaussian distributions (Gaussian 1 in blue; Gaussian 2 in pink) across the entire population according to the Akaike Information Criterion (AIC). Inset displays AIC values for 1, 2, and 3 Gaussians. Boundaries between distributions are determined by maximum likelihood cutoffs at 0% and 15% (horizontal dashed lines in left and right). (b) *Top,* percentages of each population (younger in orange; older in blue) in three trajectories (Awakening, Δspeech > 15%; Stabilization, 15% > Δspeech > 0; Decline, Δspeech < 0). *Bottom,* table of chi-square post hoc statistics showing significant differences in Decline and Awakening trajectories but not stabilization. (C) Same as in A (*right*), for the younger (*left*) and older (*right*) populations. Gaussian 3 indicated in red, demonstrating the emergence of a subset of the population in Decline stage after the cutoff age of 67.

(Varnet et al., 2021), these results highlight the relevance of central processes—in particular neural plasticity—as a critical factor to account for disparities across elderly hearing-aided people.

Successful Auditory Rehabilitation Relies on Adaptive Plasticity

Much of what is known about plasticity related to sensory deprivation comes from the literature on cochlear implantation outcomes (McKay, 2018; Stropahl et al., 2016). Wearing hearing aids slows down the negative influence of severe to profound hearing loss on cochlear implantation outcome (Lazard, Vincent, et al., 2012). It is assumed that maintaining the integrity and the activity of auditory sensorineural transmission prevents maladaptive plasticity and helps its reversal if installed (Glick & Sharma, 2020; Lazard & Giraud, 2017). In children and adults below 65 years, plasticity plays a major role in the benefits of auditory rehabilitation (Glick & Sharma, 2017; McKay, 2018; Stropahl et al., 2016). Plasticity due to cochlear implantation potentiates physiological hemispheric and regional specialization in congenital deafness (Kral et al., 2016; Lazard, Giraud, et al., 2012; Lee et al., 2001; Sharma et al., 2009). In postlingual deafness, plasticity underpins the learning curve observed during the months following surgery (Blamey et al., 1996, 2013; Giraud, Price, Graham, Truy, et al., 2001). Auditory outcomes rely in part on general clinical predictors (Lazard, Vincent, et al., 2012), on the type of compensation or reorganization strategy developed at the central level during deafness (Chen et al., 2017; Han et al., 2019; Lazard et al., 2014; Lazard & Giraud, 2017; Sandmann et al., 2012; Strelnikov et al., 2013; Stropahl et al., 2015), and on the capability to reverse or potentiate reorganization after implantation (Anderson et al., 2016; Glick & Sharma, 2020; Rouger et al., 2012).

Aging is Associated with Poorer Auditory Outcomes After Rehabilitation

In the current data, across age ranges from 17 to 93 years all subjects improved on average their speech understanding with the CI from 6 to 24 months (Figure 1(a)). However, the relative gain (learning) was significantly lower as recipient age increased and after 67 years decreased even further with age (Figure 1(a) and (b), Table 1, interaction session*age [$p < .001$] and interaction age range*session*age at implantation [$p < .001$]). As this learning relates at least in part to plasticity (Blamey et al., 1996; Giraud et al., 2000; Giraud, Price, Graham, Truy, et al., 2001; Lazard, Vincent, et al., 2012; McKay, 2018), we may, therefore, hypothesize that plasticity changes were more limited in the older than in the younger population. Aging *per se* may diminish plasticity, owing to natural connection loss and nerve degeneration in the central nervous system, and modification of the excitation–inhibition balance (Lazard, Collette, et al., 2012; Ouda et al., 2015; Thiel et al., 2006). Within the peripheral auditory system, cochlear hair cells and peripheral auditory nerve axons degenerate, along with strial atrophy (Paplou et al., 2021; Viana et al., 2015). Although brain atrophy is

a natural part of healthy aging (Long et al., 2012; Walhovd et al., 2005; Zheng et al., 2019) when associated with hearing loss, age-related volumetric decline is greater than expected in the temporal lobes, hippocampus, and entorhinal cortex (Armstrong et al., 2019; Belkhiria et al., 2020; Neuschwander et al., 2019). Although aging might be sufficient to account for limited improvement after implantation at 67 years and more, the progression profiles, as defined by the Gaussian mixture model and Chi-square test (see Figure 2), were too different between the two groups and may invite an alternative hypothesis.

Decreased Plasticity and Altered Cognitive Functions Contribute to the Variability of the Learning Curve in Older Subjects

Considering the data shown in Figure 2, we propose three different cognitive trajectories after implantation, implicating different profiles of plasticity. These profiles are hypothetical: they are based on speech performance gain, used here as a proxy of patients' cognitive progression in time, as no specific cognitive assessment was performed in this dataset. Yet, the subjects were controlled for the degree of hearing loss, as by definition all recipients presented with severe to profound hearing loss (Lin, Ferrucci, et al., 2011; Lin, Metter, et al., 2011). Of note, these hypotheses focus on trajectories of plasticity rather than absolute speech performance, because whether preoperative cognitive abilities and postoperative speech performance correlate with the aging population remains unclear (Heydebrand et al., 2007; Völter et al., 2018).

Awakening. Subjects within this profile increased their speech gain by more than 15% between 6 and 24 months after implantation. However, the Older subjects were significantly less represented (46% vs. 60% in the Younger group, Figure 2 and Chi-square test). Beneficial plasticity could be engaged and trained despite their age (Dziemian et al., 2021; Kelly et al., 2014; Mahncke et al., 2006; Tardif & Simard, 2011), but only 5% of the Older group showed a gain above 50% *versus* 16% in the Younger group. As shown by Chen et al. (2016) in an fMRI language processing study, the extent of activations in the auditory brain networks is similar in aged-matched groups of normal hearing and presbycusis elderly subjects. Yet, this magnitude is decreased compared to younger controls. Measuring auditory activations (fMRI) in nonrehabilitated hearing-impaired subjects over 65 years, age-matched and young normal hearing controls, Profant et al. (2015) showed a greater extent of auditory cortical activation including abnormal recruitment of the right temporal cortex in the older subjects, irrespective of the hearing status. Although not fully in accordance (increase vs. decrease recruitment), these observations are in favor of a modified central auditory processing with aging and may account for the smaller proportion of older subjects with gains superior to 15%.

We refer to this progressing profile as *Awakening*: The learning curve is consistent with the reversion and positive development of central changes induced by rehabilitation. One example of such plastic change comes from functional neuroimaging results showing the reactivation of primary and secondary auditory cortices and potentiation of audiovisual synergy, that is, lipreading from the first to the third year after implantation (Giraud, Price, Graham, & Frackowiak, 2001; Lazard & Giraud, 2017; Rouger et al., 2012; Strelnikov et al., 2013). The detrimental effects of deafness on cognition, through social isolation, depression, and cognitive burden, can reverse as a result of rewiring (Lin & Albert, 2014; Mudar & Husain, 2016; Pichora-Fuller, 2003). Subjects in this group face healthy aging despite sensory deprivation. This is in accordance with Giroud et al. (2017), who showed a decrease in processing effort, assessed by EEG recordings, in a three-month prospective study of syllable identification task in healthy old adults (60–77 years) when using conventional hearing aids.

Stabilization/Counteracting. Subjects within this profile maintained or slightly increased their speech gain after 2 years of CI use (gain between 0 and 15%). The proportions were the same between the two groups (around 30%). This group benefited from implantation but is arguably less inclined to develop a functional reorganization/mobilization of their auditory networks. Relating this to plasticity, this profile might result from maladaptive, poorly reversible deafness-driven plasticity, and/or from an abnormally low level of central adaptation to rehabilitation (diminished propensity to reactivate auditory networks and connectivity), regardless of age (Anderson et al., 2016; Lazard et al., 2010; Lazard & Giraud, 2017; Lazard, Giraud, et al., 2012; Rouger et al., 2012).

An alternative analysis of the data may question this equal proportion between the two groups: we could have expected older subjects to be more numerous in this profile (as explained earlier: Chen et al., 2016; Profant et al., 2015). Conversely, this shift operated toward the declining performance profile (see below for hypotheses).

More generally, the *Awakening* and *Stabilization* profiles are dominant in both populations (Older 78% and Younger 89%). This may explain why some studies have found no difference in the outcome of cochlear implantation between a reference population and older subjects, based on more limited number of subjects.

Decline. The third profile corresponds to subjects who show a regression of speech scores over two years of implantation. Although smaller in the reference population (11%), they represent 23% of the Older group. A plausible explanation for the younger group may be that maladaptive plasticity strengthens, the brain is unable to adapt to auditory rewiring (Anderson et al., 2016). Specific etiologies, epigenetic factors, and/or loss in speech therapy follow-up may participate.

We may hypothesize that in the Stabilization and Decline profiles, cochlear implantation acts as a stabilizer against other processes that would tend to diminish speech

understanding outcome over time, and by extension cognitive abilities. In some cases, the lack of improvement would be a marker of central and peripheral dysfunction of the same disease (Murphy et al., 2018; Swords et al., 2018). This hypothesis could be formally tested, for instance by assessing the impact of hearing impairment—and the consequences of hearing rehabilitation—on electrophysiological signatures of central cognitive processes (Näätänen et al., 2011). In this view, auditory rehabilitation would induce positive therapeutic effects by counteracting the evolving process and ultimately protect against mild cognitive degeneration (Mosnier et al., 2018). In line with this, the association between Alzheimer's disease and nonrehabilitated hearing loss predicts more rapid cognitive decline (Peters et al., 1988). Such a benefit might extend, beyond speech perception and quality of life, to cognitive functions such as attention, working memory, and long-term memory (Rönnberg et al., 2013; Völter et al., 2018).

Finally, when a decline in performance is observed, central processes evolving independently of each other may be intertwined, against which auditory rehabilitation has no action. We suppose a co-occurrence of cognitive impairments resulting in speech understanding difficulties leading to the worsening of cochlear implant outcome. Thus, for example, Knopke et al. (2021) found that preexisting white matter lesions constitute an independent risk factor of degraded cochlear implant speech scores, which evolve independently of the duration of deafness. Among the risk factors, common microvascular disease factors such as high blood pressure have been identified as being involved in the degradation of white matter connectivity, which has a negative impact on executive functions in addition to aging (Hoagey et al., 2021).

Consistent with our observations, a recent study comparing a large number of rehabilitated hearing-impaired and normal-hearing subjects ($n = 459$, age = 42–92) confirmed a wider heterogeneity in the hearing-impaired group (Varnet et al., 2021). As audibility and age do not seem to account for this variability in their statistical model, these results highlight that central processing deficits might be involved.

Conclusion

Subjects over 70 years of age do not show the same absolute benefit nor the same learning curve after 2 years of cochlear implantation as younger subjects. Three different hypothetic profiles of plasticity may explain these disparities: (1) the Awakening profile reflects the reversal of the central changes induced by deafness, although to a lesser extent because of healthy aging, (2) in the Stabilization/Counteracting profile, cochlear implantation serves as a stabilizer against processes that would tend to decrease speech understanding outcomes as well as cognitive abilities over time and (3) the Decline profile represents additional independently evolving central processes, for which auditory rehabilitation cannot prevent a pejorative evolution. Considering these plasticity changes, adding specific interventions that promote exogenous or endogenous attentional functions to the more conventional speech therapy may ultimately help guide hearing-impaired subjects to better cope with normal or pathological central aging.

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References

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *19*(6), 716–723. https://doi.org/10.1109/TAC.1974.1100705

Amieva, H., Ouvrard, C., Giulioli, C., Meillon, C., Rullier, L., & Dartigues, J.-F. (2015). Self-reported hearing loss, hearing aids, and cognitive decline in elderly adults: A 25-year study. *Journal of the American Geriatrics Society*, *63*(10), 2099–2104. https://doi.org/10.1111/jgs.13649

Anderson, C. A., Lazard, D. S., & Hartley, D. E. H. (2016). Plasticity in bilateral superior temporal cortex: Effects of deafness and cochlear implantation on auditory and visual speech processing. *Hearing Research*, *343*, 138–149. https://doi.org/10.1016/j.heares.2016.07.013

Armstrong, N. M., An, Y., Doshi, J., Erus, G., Ferrucci, L., Davatzikos, C., Deal, J. A., Lin, F. R., & Resnick, S. M. (2019). Association of midlife hearing impairment with late-life temporal lobe volume loss. *JAMA Otolaryngology–Head & Neck Surgery*, *145*(9), 794–802. https://doi.org/10.1001/jamaoto.2019.1610

Armstrong, N. M., An, Y., Ferrucci, L., Deal, J. A., Lin, F. R., & Resnick, S. M. (2020). Temporal sequence of hearing impairment and cognition in the Baltimore longitudinal study of aging. *Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *75*(3), 574–580. https://doi.org/10.1093/gerona/gly268

Belkhiria, C., Vergara, R. C., San Martin, S., Leiva, A., Martinez, M., Marcenaro, B., Andrade, M., Delano, P. H., & Delgado, C.

(2020). Insula and amygdala atrophy are associated with functional impairment in subjects with presbycusis. *Frontiers in Aging Neuroscience*, *12*, 102. https://doi.org/10.3389/fnagi.2020.00102

Blamey, P., Arndt, P., Bergeron, F., Bredberg, G., Brimacombe, J., Facer, G., Larky, J., Lindstrom, B., Nedzelski, J., Peterson, A., Shipp, D., Staller, S., & Whitford, L. (1996). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants. *Audiology and Neurotology*, *1*(5), 293–306. https://doi.org/10.1159/000259212

Blamey, P., Artieres, F., Baskent, D., Bergeron, F., Beynon, A., Burke, E., Dillier, N., Dowell, R., Fraysse, B., Gallego, S., Govaerts, P. J., Green, K., Huber, A. M., Kleine-Punte, A., Maat, B., Marx, M., Mawman, D., Mosnier, I., O'Connor, A. F., … D. S Lazard. (2013). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants: An update with 2251 patients. *Audiology and Neurotology*, *18*(1), 36–47. https://doi.org/10.1159/000343189

Blamey, P. J., Maat, B., Başkent, D., Mawman, D., Burke, E., Dillier, N., Beynon, A., Kleine-Punte, A., Govaerts, P. J., Skarzynski, P. H., Huber, A. M., Sterkers-Artières, F., Van de Heyning, P., O'Leary, S., Fraysse, B., Green, K., Sterkers, O., Venail, F., Skarzynski, H., … D. S Lazard. (2015). A retrospective multicenter study comparing speech perception outcomes for bilateral implantation and bimodal rehabilitation. *Ear & Hearing*, *36*(4), 408–416. https://doi.org/10.1097/AUD.0000000000000150

Brewster, K. K., Pavlicova, M., Stein, A., Chen, M., Chen, C., Brown, P. J., Roose, S. P., Kim, A. H., Golub, J. S., Brickman, A., Galatioto, J., Kuhlmey, M., & Rutherford, B. R. (2020). A pilot randomized controlled trial of hearing aids to improve mood and cognition in older adults. *International Journal of Geriatric Psychiatry*, *35*(8), 842–850. https://doi.org/10.1002/gps.5311

Carlson, M. L., Breen, J. T., Gifford, R. H., Driscoll, C. L. W., Neff, B. A., Beatty, C. W., Peterson, A. M., & Olund, A. P. (2010). Cochlear implantation in the octogenarian and nonagenarian. *Otology & Neurotology*, *31*(8), 1343–1349. https://doi.org/10.1097/MAO.0b013e3181edb69d

Chen, L.-C., Puschmann, S., & Debener, S. (2017). Increased cross-modal functional connectivity in cochlear implant users. *Scientific Reports*, *7*(1), 10043. https://doi.org/10.1038/s41598-017-10792-2

Chen, X., Wang, M., Deng, Y., Liang, Y., Li, J., & Chen, S. (2016). Language processing of auditory cortex revealed by functional magnetic resonance imaging in presbycusis patients. *Acta Oto-Laryngologica*, *136*(2), 113–119. https://doi.org/10.3109/00016489.2015.1049662

Davis, A., McMahon, C. M., Pichora-Fuller, K. M., Russ, S., Lin, F., Olusanya, B. O., Chadha, S., & Tremblay, K. L. (2016). Aging and hearing health: The life-course approach. *The Gerontologist*, *56*(Suppl 2), S256–S267. https://doi.org/10.1093/geront/gnw033

Deal, J. A., Betz, J., Yaffe, K., Harris, T., Purchase-Helzner, E., Satterfield, S., Pratt, S., Govil, N., Simonsick, E. M., & Lin, F. R., & Health ABC Study Group. (2017). Hearing impairment and incident dementia and cognitive decline in older adults: The Health ABC Study. *Journals of Gerontology Series A, Biological Sciences and Medical Sciences*, *72*(5), 703–709. https://doi.org/10.1093/gerona/glw069

Dziemian, S., Appenzeller, S., von Bastian, C. C., Jäncke, L., & Langer, N. (2021). Working memory training effects on white matter integrity in young and older adults. *Frontiers in Human Neuroscience*, *15*, https://doi.org/10.3389/fnhum.2021.605213

Friedland, D. R., Runge-Samuelson, C., Baig, H., & Jensen, J. (2010). Case-control analysis of cochlear implant performance in elderly patients. *Archives of Otolaryngology–Head & Neck Surgery*, *136*(5), 432–438. https://doi.org/10.1001/archoto.2010.57

Füllgrabe, C., & Rosen, S. (2016). On the (un)importance of working memory in speech-in-noise processing for listeners with normal hearing thresholds. *Frontiers in Psychology*, *7*, 1268. https://doi.org/10.3389/fpsyg.2016.01268

Gallacher, J., Ilubaera, V., Ben-Shlomo, Y., Bayer, A., Fish, M., Babisch, W., & Elwood, P. (2012). Auditory threshold, phonologic demand, and incident dementia. *Neurology*, *79*(15), 1583–1590. https://doi.org/10.1212/WNL.0b013e31826e263d

Giourgas, A., Durisin, M., Lesinski-Schiedat, A., Illg, A., & Lenarz, T. (2021). Auditory performance in a group of elderly patients after cochlear implantation. *European Archives of Otorhinolaryngology*, *278*(11), 4295–4303. https://doi.org/10.1007/s00405-020-06566-8

Giraud, A. L., Price, C. J., Graham, J. M., & Frackowiak, R. S. (2001). Functional plasticity of language-related brain areas after cochlear implantation. *Brain*, *124*(Pt 7), 1307–1316. https://doi.org/10.1093/brain/124.7.1307

Giraud, A. L., Price, C. J., Graham, J. M., Truy, E., & Frackowiak, R. S. (2001). Cross-modal plasticity underpins language recovery after cochlear implantation. *Neuron*, *30*(3), 657–664. https://doi.org/10.1016/S0896-6273(01)00318-X

Giraud, A. L., Truy, E., Frackowiak, R. S., Gregoire, M. C., Pujol, J. F., & Collet, L. (2000). Differential recruitment of the speech processing system in healthy subjects and rehabilitated cochlear implant patients. *Brain*, *123*(Pt 7), 1391–1402. https://doi.org/10.1093/brain/123.7.1391

Giroud, N., Lemke, U., Reich, P., Matthes, K. L., & Meyer, M. (2017). The impact of hearing aids and age-related hearing loss on auditory plasticity across three months—An electrical neuroimaging study. *Hearing Research*, *353*, 162–175. https://doi.org/10.1016/j.heares.2017.06.012

Glick, H. A., & Sharma, A. (2020). Cortical neuroplasticity and cognitive function in early-stage, mild-moderate hearing loss: Evidence of neurocognitive benefit from hearing aid use. *Frontiers in Neuroscience*, *14*, 93. https://doi.org/10.3389/fnins.2020.00093

Glick, H., & Sharma, A. (2017). Cross-modal plasticity in developmental and age-related hearing loss: Clinical implications. *Hearing Research*, *343*, 191–201. https://doi.org/10.1016/j.heares.2016.08.012

Goman, A. M., & Lin, F. R. (2016). Prevalence of hearing loss by severity in the United States. *American Journal of Public Health*, *106*(10), 1820–1822. https://doi.org/10.2105/AJPH.2016.303299

Gurgel, R. K., Ward, P. D., Schwartz, S., Norton, M. C., Foster, N. L., & Tschanz, J. T. (2014). Relationship of hearing loss and dementia: A prospective, population-based study. *Otology & Neurotology*, *35*(5), 775–781. https://doi.org/10.1097/MAO.0000000000000313

Han, J.-H., Lee, H.-J., Kang, H., Oh, S.-H., & Lee, D. S. (2019). Brain plasticity can predict the cochlear implant outcome in adult-onset deafness. *Frontiers in Human Neuroscience*, *13*, 38. https://doi.org/10.3389/fnhum.2019.00038

Hast, A., Schlücker, L., Digeser, F., Liebscher, T., & Hoppe, U. (2015). Speech perception of elderly cochlear implant users under different

noise conditions. *Otology & Neurotology*, *36*(10), 1638–1643. https://doi.org/10.1097/MAO.0000000000000883

Heydebrand, G., Hale, S., Potts, L., Gotter, B., & Skinner, M. (2007). Cognitive predictors of improvements in adults' spoken word recognition six months after cochlear implant activation. *Audiology and Neurotology*, *12*(4), 254–264. https://doi.org/10.1159/000101473

Hoagey, D. A., Lazarus, L. T. T., Rodrigue, K. M., & Kennedy, K. M. (2021). The effect of vascular health factors on white matter microstructure mediates age-related differences in executive function performance. *Cortex*, *141*, 403–420. https://doi.org/10.1016/j.cortex.2021.04.016

Holden, L. K., Finley, C. C., Firszt, J. B., Holden, T. A., Brenner, C., Potts, L. G., Gotter, B. D., Vanderhoof, S. S., Mispagel, K., Heydebrand, G., & Skinner, M. W. (2013). Factors affecting open-set word recognition in adults with cochlear implants. *Ear & Hearing*, *34*(3), 342–360. https://doi.org/10.1097/AUD.0b013e3182741aa7

Keithley, E. M. (2020). Pathology and mechanisms of cochlear aging. *Journal of Neuroscience Research*, *98*(9), 1674–1684. https://doi.org/10.1002/jnr.24439

Kelly, M. E., Loughrey, D., Lawlor, B. A., Robertson, I. H., Walsh, C., & Brennan, S. (2014). The impact of cognitive training and mental stimulation on cognitive and everyday functioning of healthy older adults: A systematic review and meta-analysis. *Ageing Research Reviews*, *15*, 28–43. https://doi.org/10.1016/j.arr.2014.02.004

Knopke, S., Gräbel, S., Förster-Ruhrmann, U., Mazurek, B., Szczepek, A. J., & Olze, H. (2016). Impact of cochlear implantation on quality of life and mental comorbidity in patients aged 80 years. *The Laryngoscope*, *126*(12), 2811–2816. https://doi.org/10.1002/lary.25993

Knopke, S., Schubert, A., Häussler, S. M., Gräbel, S., Szczepek, A. J., & Olze, H. (2021). Improvement of working memory and processing speed in patients over 70 with bilateral hearing impairment following unilateral cochlear implantation. *Journal of Clinical Medicine*, *10*(15), 3421. https://doi.org/10.3390/jcm10153421

Kral, A., Kronenberger, W. G., Pisoni, D. B., & O'Donoghue, G. M. (2016). Neurocognitive factors in sensory restoration of early deafness: A connectome model. *The Lancet Neurology*, *15*(6), 610–621. https://doi.org/10.1016/S1474-4422(16)00034-X

Lazard, D. S., Collette, J. L., & Perrot, X. (2012). Speech processing: From peripheral to hemispheric asymmetry of the auditory system. *The Laryngoscope*, *122*(1), 167–173. https://doi.org/10.1002/lary.22370

Lazard, D. S., & Giraud, A.-L. (2017). Faster phonological processing and right occipito-temporal coupling in deaf adults signal poor cochlear implant outcome. *Nature Communications*, *8*(1), 14872. https://doi.org/10.1038/ncomms14872

Lazard, D. S., Giraud, A. L., Gnansia, D., Meyer, B., & Sterkers, O. (2012). Understanding the deafened brain: Implications for cochlear implant rehabilitation. *European Annals of Otorhinolaryngology, Head and Neck Diseases*, *129*(2), 98–103. https://doi.org/10.1016/j.anorl.2011.06.001

Lazard, D. S., Innes-Brown, H., & Barone, P. (2014). Adaptation of the communicative brain to post-lingual deafness. Evidence from functional imaging. *Hearing Research*, *307*, 136–143. https://doi.org/10.1016/j.heares.2013.08.006

Lazard, D. S., Lee, H. J., Gaebler, M., Kell, C. A., Truy, E., & Giraud, A. L. (2010). Phonological processing in post-lingual deafness and cochlear implant outcome. *Neuroimage*, *49*(4), 3443–3451. https://doi.org/10.1016/j.neuroimage.2009.11.013

Lazard, D. S., Vincent, C., Venail, F., Van de Heyning, P., Truy, E., Sterkers, O., Skarzynski, P. H., Skarzynski, H., Schauwers, K., O'Leary, S., Mawman, D., Maat, B., Kleine-Punte, A., Huber, A. M., Green, K., Govaerts, P. J., Fraysse, B., Dowell, R., & Dillier, N., … P. J Blamey. (2012). Pre-, per- and postoperative factors affecting performance of postlinguistically deaf adults using cochlear implants: A new conceptual model over time. *PLoS One*, *7*(11), e48739. https://doi.org/10.1371/journal.pone.0048739

Lee, A. K., Larson, E., & Miller, C. W. (2018). Effects of hearing loss on maintaining and switching attention. *Acta Acustica United with Acustica*, *104*(5), 787–791. https://doi.org/10.3813/aaa.919224

Lee, D. S., Lee, J. S., Oh, S. H., Kim, S. K., Kim, J. W., Chung, J. K., Lee, M. C., & Kim, C. S. (2001). Cross-modal plasticity and cochlear implants. *Nature*, *409*(6817), 149–150. https://doi.org/10.1038/35051653

Lenarz, M., Sönmez, H., Joseph, G., Büchner, A., & Lenarz, T. (2012). Cochlear implant performance in geriatric patients. *The Laryngoscope*, *122*(6), 1361–1365. https://doi.org/10.1002/lary.23232

Lin, F. R., & Albert, M. (2014). Hearing loss and dementia—Who is listening? *Aging & Mental Health*, *18*(6), 671–673. https://doi.org/10.1080/13607863.2014.915924

Lin, F. R., Ferrucci, L., Metter, E. J., An, Y., Zonderman, A. B., & Resnick, S. M. (2011). Hearing loss and cognition in the Baltimore Longitudinal Study of Aging. *Neuropsychology*, *25*(6), 763–770. https://doi.org/10.1037/a0024238

Lin, F. R., Metter, E. J., O'Brien, R. J., Resnick, S. M., Zonderman, A. B., & Ferrucci, L. (2011). Hearing loss and incident dementia. *Archives of Neurology*, *68*(2), 214–220. https://doi.org/10.1001/archneurol.2010.362

Lin, F. R., Yaffe, K., Xia, J., Xue, Q.-L., Harris, T. B., Purchase-Helzner, E., Satterfield, S., Ayonayon, H. N., Ferrucci, L., & Simonsick, E. M., & Health ABC Study Group. (2013). Hearing loss and cognitive decline in older adults. *JAMA Internal Medicine*, *173*(4), 293. https://doi.org/10.1001/jamainternmed.2013.1868

Livingston, G., Huntley, J., Sommerlad, A., Ames, D., Ballard, C., Banerjee, S., Brayne, C., Burns, A., Cohen-Mansfield, J., Cooper, C., Costafreda, S. G., Dias, A., Fox, N., Gitlin, L. N., Howard, R., Kales, H. C., Kivimäki, M., Larson, E. B., Ogunniyi, A., … N Mukadam. (2020). Dementia prevention, intervention, and care: 2020 report of the Lancet Commission. *The Lancet*, *396*(10248), 413–446. https://doi.org/10.1016/S0140-6736(20)30367-6

Long, X., Liao, W., Jiang, C., Liang, D., Qiu, B., & Zhang, L. (2012). Healthy aging: An automatic analysis of global and regional morphological alterations of human brain. *Academic Radiology*, *19*(7), 785–793. https://doi.org/10.1016/j.acra.2012.03.006

Loughrey, D. G., Kelly, M. E., Kelley, G. A., Brennan, S., & Lawlor, B. A. (2018). Association of age-related hearing loss with cognitive function, cognitive impairment, and dementia: A systematic review and meta-analysis. *JAMA Otolaryngology–Head & Neck Surgery*, *144*(2), 115–126. https://doi.org/10.1001/jamaoto.2017.2513

Mahncke, H. W., Connor, B. B., Appelman, J., Ahsanuddin, O. N., Hardy, J. L., Wood, R. A., Joyce, N. M., Boniske, T., Atkins, S. M., & Merzenich, M. M. (2006). Memory enhancement in healthy older adults using a brain plasticity-based training program: A randomized, controlled study. *Proceedings of the*

National Academy of Sciences of the United States of America, *103*(33), 12523–12528. https://doi.org/10.1073/pnas.0605194103

McKay, C. M. (2018). Brain plasticity and rehabilitation with a cochlear implant. *Advances in Otorhinolaryngology*, *81*, 57–65. https://doi.org/10.1159/000485586

Moberly, A. C., Bates, C., Harris, M. S., & Pisoni, D. B. (2016). The enigma of poor performance by adults with cochlear implants. *Otology & Neurotology*, *37*(10), 1522–1528. https://doi.org/10.1097/MAO.0000000000001211

Moberly, A. C., Houston, D. M., & Castellanos, I. (2016). Non-auditory neurocognitive skills contribute to speech recognition in adults with cochlear implants. *Laryngoscope Investigative Otolaryngology*, *1*(6), 154–162. https://doi.org/10.1002/lio2.38

Mosnier, I., Vanier, A., Bonnard, D., Lina-Granade, G., Truy, E., Bordure, P., Godey, B., Marx, M., Lescanne, E., Venail, F., Poncet, C., Sterkers, O., & Belmin, J. (2018). Long-term cognitive prognosis of profoundly deaf older adults after hearing rehabilitation using cochlear implants. *Journal of the American Geriatrics Society*, *66*(8), 1553–1561. https://doi.org/10.1111/jgs.15445

Mudar, R. A., & Husain, F. T. (2016). Neural alterations in acquired age-related hearing loss. *Frontiers in Psychology*, *7*, 828. https://doi.org/10.3389/fpsyg.2016.00828

Murphy, C. F. B., Rabelo, C. M., Silagi, M. L., Mansur, L. L., Bamiou, D. E., & Schochat, E. (2018). Auditory processing performance of the middle-aged and elderly: Auditory or cognitive decline? *Journal of the American Academy of Audiology*, *29*(1), 5–14. https://doi.org/10.3766/jaaa.15098

Näätänen, R., Kujala, T., Kreegipuu, K., Carlson, S., Escera, C., Baldeweg, T., & Ponton, C. (2011). The mismatch negativity: An index of cognitive decline in neuropsychiatric and neurological diseases and in ageing. *Brain: A Journal of Neurology*, *134*(Pt 12), 3435–3453. https://doi.org/10.1093/brain/awr064

Neuschwander, P., Hänggi, J., Zekveld, A. A., & Meyer, M. (2019). Cortical thickness of left Heschl's gyrus correlates with hearing acuity in adults—A surface-based morphometry study. *Hearing Research*, *384*, 107823. https://doi.org/10.1016/j.heares.2019.107823

Nittrouer, S., Lowenstein, J. H., Wucinich, T., & Moberly, A. C. (2016). Verbal working memory in older adults: The roles of phonological capacities and processing speed. *Journal of Speech, Language, and Hearing Research*, *59*(6), 1520–1532. https://doi.org/10.1044/2016_JSLHR-H-15-0404

Ouda, L., Profant, O., & Syka, J. (2015). Age-related changes in the central auditory system. *Cell and Tissue Research*, *361*(1), 337–358. https://doi.org/10.1007/s00441-014-2107-2

Paplou, V., Schubert, N. M. A., & Pyott, S. J. (2021). Age-related changes in the cochlea and vestibule: Shared patterns and processes. *Frontiers in Neuroscience*, *15*, 680856. https://doi.org/10.3389/fnins.2021.680856

Peters, C. A., Potter, J. F., & Scholer, S. G. (1988). Hearing impairment as a predictor of cognitive decline in dementia. *Journal of the American Geriatrics Society*, *36*(11), 981–986. https://doi.org/10.1111/j.1532-5415.1988.tb04363.x

Pichora-Fuller, M. K. (2003). Cognitive aging and auditory information processing. *International Journal of Audiology*, *42*(Suppl 2), 2S26–2S32. https://doi.org/10.3109/14992020309074641

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W. Y., Humes, L. E., Lemke, U., Lunner, T., Matthen, M., Mackersie, C. L., Naylor, G., Phillips, N. A., Richter, M., Rudner, M., Sommers, M. S., Tremblay, K. L., & Wingfield, A. (2016). Hearing impairment and cognitive energy. *Ear & Hearing*, *37*(1), 5S–27S. https://doi.org/10.1097/AUD.0000000000000312

Profant, O., Tintěra, J., Balogová, Z., Ibrahim, I., Jilek, M., & Syka, J. (2015). Functional changes in the human auditory cortex in ageing. *PLoS One*, *10*(3), e0116692. https://doi.org/10.1371/journal.pone.0116692

Rouger, J., Lagleyre, S., Demonet, J. F., Fraysse, B., Deguine, O., & Barone, P. (2012). Evolution of crossmodal reorganization of the voice area in cochlear-implanted deaf patients. *Human Brain Mapping*, *33*(8), 1929–1940. https://doi.org/10.1002/hbm.21331

Rönnberg, J., Lunner, T., Zekveld, A., Sörqvist, P., Danielsson, H., Lyxell, B., Dahlström, Ö, Signoret, C., Stenfelt, S., Pichora-Fuller, M. K., & Rudner, M. (2013). The Ease of Language Understanding (ELU) model: Theoretical, empirical, and clinical advances. *Frontiers in Systems Neuroscience*, *7*, https://doi.org/10.3389/fnsys.2013.00031

Sandmann, P., Dillier, N., Eichele, T., Meyer, M., Kegel, A., Pascual-Marqui, R. D., Marcar, V. L., Jancke, L., & Debener, S. (2012). Visual activation of auditory cortex reflects maladaptive plasticity in cochlear implant users. *Brain*, *135*(Pt 2), 555–568. https://doi.org/10.1093/brain/awr329

Seabold, S., & Perktold, J. (2010). Statsmodels: Econometric and statistical modeling with Python. 92-96. https://doi.org/10.25080/Majora-92bf1922-011

Sharma, A., Nash, A. A., & Dorman, M. (2009). Cortical development, plasticity and re-organization in children with cochlear implants. *Journal of Communication Disorders*, *42*(4), 272–279. https://doi.org/10.1016/j.jcomdis.2009.03.003

Sharma, R. K., Lalwani, A. K., & Golub, J. S. (2020). Prevalence and severity of hearing loss in the older old population. *JAMA Otolaryngology–Head & Neck Surgery*, *146*(8), 762–763. https://doi.org/10.1001/jamaoto.2020.0900

Solheim, J., Gay, C., & Hickson, L. (2018). Older adults' experiences and issues with hearing aids in the first six months after hearing aid fitting. *International Journal of Audiology*, *57*(1), 31–39. https://doi.org/10.1080/14992027.2017.1380849

Solheim, J., & Hickson, L. (2017). Hearing aid use in the elderly as measured by datalogging and self-report. *International Journal of Audiology*, *56*(7), 472–479. https://doi.org/10.1080/14992027.2017.1303201

Strelnikov, K., Rouger, J., Demonet, J. F., Lagleyre, S., Fraysse, B., Deguine, O., & Barone, P. (2013). Visual activity predicts auditory recovery from deafness after adult cochlear implantation. *Brain*, *136*(12), 3682–3695. https://doi.org/10.1093/brain/awt274

Stropahl, M., Chen, L.-C., & Debener, S. (2016). Cortical reorganization in postlingually deaf cochlear implant users: Intra-modal and cross-modal considerations. *Hearing Research 343*, 128–137. https://doi.org/10.1016/j.heares.2016.07.005

Stropahl, M., Plotz, K., Schönfeld, R., Lenarz, T., Sandmann, P., Yovel, G., De Vos, M., & Debener, S. (2015). Cross-modal reorganization in cochlear implant users: Auditory cortex contributes to visual face processing. *NeuroImage*, *121*, 159–170. https://doi.org/10.1016/j.neuroimage.2015.07.062

Swords, G. M., Nguyen, L. T., Mudar, R. A., & Llano, D. A. (2018). Auditory system dysfunction in Alzheimer disease and its prodromal states: A review. *Ageing Research Reviews*, *44*, 49–59. https://doi.org/10.1016/j.arr.2018.04.001

Tardif, S., & Simard, M. (2011). Cognitive stimulation programs in healthy elderly: A review. *International Journal of Alzheimer's Disease*, *2011*, 378934. https://doi.org/10.4061/2011/378934

Thiel, A., Schumacher, B., Wienhard, K., Gairing, S., Kracht, L. W., Wagner, R., Haupt, W. F., & Heiss, W. D. (2006). Direct demonstration of transcallosal disinhibition in language networks. *Journal of Cerebral Blood Flow & Metabolism*, *26*(9), 1122–1127. https://doi.org/10.1038/sj.jcbfm.9600350

Varnet, L., Léger, A. C., Boucher, S., Bonnet, C., Petit, C., & Lorenzi, C. (2021). Contributions of age-related and audibility-related deficits to aided consonant identification in presbycusis: A causal-inference analysis. *Frontiers in Aging Neuroscience*, *13*, 640522. https://doi.org/10.3389/fnagi.2021.640522

Viana, L. M., O'Malley, J. T., Burgess, B. J., Jones, D. D., Oliveira, C. A. C. P., Santos, F., Merchant, S. N., Liberman, L. D., & Liberman, M. C. (2015). Cochlear neuropathy in human presbycusis: Confocal analysis of hidden hearing loss in post-mortem tissue. *Hearing Research*, *327*, 78–88. https://doi.org/10.1016/j.heares.2015.04.014

Völter, C., Götze, L., Dazert, S., Falkenstein, M., & Thomas, J. P. (2018). Can cochlear implantation improve neurocognition in the aging population? *Clinical Interventions in Aging*, *13*, 701–712. https://doi.org/10.2147/CIA.S160517

Walhovd, K. B., Fjell, A. M., Reinvang, I., Lundervold, A., Dale, A. M., Eilertsen, D. E., Quinn, B. T., Salat, D., Makris, N., & Fischl, B. (2005). Effects of age on volumes of cortex, white matter and subcortical structures. *Neurobiology of Aging*, *26*(9), 1261–1270; discussion 1275-1278. https://doi.org/10.1016/j.neurobiolaging.2005.05.020

Zheng, F., Liu, Y., Yuan, Z., Gao, X., He, Y., Liu, X., Cui, D., Qi, R., Chen, T., & Qiu, J. (2019). Age-related changes in cortical and subcortical structures of healthy adult brains: A surface-based morphometry study. *Journal of Magnetic Resonance Imaging*, *49*(1), 152–163. https://doi.org/10.1002/jmri.26037