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Poor Performer: A Distinct Entity in Cochlear Implant Users?

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Keywords

Cochlear implantation · Poor performer · Speech performance · Neurocognitive testing · Word retrieval

Abstract

Introduction: Several factors are known to influence speech perception in cochlear implant (CI) users. To date, the underlying mechanisms have not yet been fully clarified. Although many CI users achieve a high level of speech perception, a small percentage of patients does not or only slightly benefit from the CI (poor performer, PP). In a previous study, PP showed significantly poorer results on nonauditory-based cognitive and linguistic tests than CI users with a very high level of speech understanding (star performer, SP). We now investigate if PP also differs from the CI user with an average performance (average performer, AP) in cognitive and linguistic performance. ***Methods:*** Seventeen adult postlingually deafened CI users with speech perception scores in quiet of 55 (9.32) % (AP) on the German Freiburg monosyllabic speech test at 65 dB underwent neurocognitive (attention, working memory, short- and long-term memory, verbal fluency, inhibition) and linguistic testing (word retrieval, lexical decision, phonological input lexicon). The results were compared to the performance of 15 PP (speech perception score of 15 [11.80] %) and 19 SP (speech perception score of 80 [4.85] %). For statistical analysis, U-Test and discrimination analysis have been done. ***Results:*** Significant differences between PP and AP were observed on linguistic tests, in Rapid Automatized Naming (RAN: $p = 0.0026$), lexical decision (LexDec: $p = 0.026$), phonological input lexicon (LEMO: $p = 0.0085$), and understanding of incomplete words (TRT: $p = 0.0024$). AP also had significantly better neurocognitive results than PP in the domains of attention (M3: $p = 0.009$) and working memory (OSPAN: $p = 0.041$; RST: $p = 0.015$) but not in delayed recall (delayed recall: $p = 0.22$), verbal fluency (verbal fluency: $p = 0.084$), and inhibition (Flanker: $p = 0.35$). In contrast, no differences were found hereby between AP and SP. Based on the TRT and the RAN, AP and PP could be separated in 100%. ***Discussion:*** The results indicate that PP constitute a distinct entity of CI users that differs even in nonauditory abilities from CI users with an average speech perception, especially with regard to rapid word retrieval either due to reduced phonological abilities or limited storage. Further studies should investigate if improved word retrieval by increased phonological and semantic training results in better speech perception in these CI users.

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Introduction

Auditory rehabilitation by cochlear implantation has become a very effective treatment option in subjects with severe-to-profound hearing loss or complete deafness. Most cochlear implant (CI) recipients achieve a high level of speech perception [Boisvert et al., 2020; Carlson, 2020; Dazert et al., 2020]. However, speech perception after cochlear implantation is highly variable [Green et al., 2007; Blamey et al., 2013; Holden et al., 2013; Tamati et al., 2020]. Despite years of experience in cochlear implantation and a series of new technological developments and efforts, there is still a number of subjects who do not or do only slightly benefit from cochlear implantation [Lenarz et al., 2012; Blamey et al., 2013; Rumeau et al., 2015; Moberly et al., 2016a].

In relation to the total number of CI users worldwide, this number might be small. However, considering the extremely negative consequences of hearing loss on each individual affected and the costs that cochlear implantation imposes on the society, there is a great need to improve speech perception outcomes in these patients [Moberly et al., 2016a; Pisoni et al., 2017; Völter et al., 2021b].

In the past, various attempts have been undertaken to explain or improve CI outcome. Those attempts often focused on improving signal quality, such as through electrode array design, number of electrodes, processing strategies, insertion depth, frequency encoding precision, and patient-related factors such as residual acoustic hearing [Summers and Leek, 1994; Henry et al., 2005; Neher et al., 2011; Scheperle and Abbas, 2015] or duration of deafness [Beyea et al., 2016; Bernhard et al., 2021]. Furthermore, auditory training which is recommended after cochlear implantation to improve speech perception was mainly based on analytic bottom-up approaches [Fu and Galvin, 2008].

In CI users, however, also top-down mechanisms are crucial for speech perception due to the need to interpret the distorted signal transmitted by the implant [Başkent, 2012; Bhargava et al., 2014; Moberly and Reed, 2019]. Candidate factors include cognitive abilities such as processing speed, working memory, inhibitory processes, and verbal fluency as well as linguistic knowledge [Salthouse, 1996; Lyxell et al., 1998; Kronenberger et al., 2014; Payne, 2014; Finke et al., 2016; Winn, 2016; Smith et al., 2019; Zhan et al., 2020].

Different ways to process phonological tasks have been described and correlated to speech outcome in CI users by fMRI [Lazard and Giraud, 2017] and in SPECT and EEG studies [Kessler et al., 2020]. Whereas CI users with higher speech performance showed additional activations of parietal and occipital regions, those with lower performance used superior frontal areas during speech processing.

So far, only very few studies have focused on the subgroup of extremely poor- or high-performing CI users analyzing some nonauditory skills [Hillyer et al., 2019; Tamati et al., 2020]. Most studies correlated speech perception and cognitive or linguistic parameters in CI users in general or in comparison to normal-hearing subjects [Heydebrand et al., 2007; Holden et al., 2013; Cosetti et al., 2016; Moberly et al., 2016b; Moberly et al., 2017; Mattingly et al., 2018; Zhan et al., 2020]. Due to the small number of poor-performing subjects, however, individual strategies in speech processing might be overlooked in studies dealing with the total CI population and a focus on extreme cases might better reveal even slight individual differences [Başkent et al., 2016; Nagels et al., 2019]. We recently compared two extreme groups, poor (poor performer, PP) and exceptionally good-performing CI users (star performer, SP), and differences of speech perception could be explained by differences in phonological and cognitive processing [Völter et al., 2020a].

Therefore, the question arose whether these differences can also distinguish PP and the large group of average-performing CI users (average performer, AP). In other words assuming that AP are the norm, are the SP or the PP the odd ones out? A stronger focus on individual differences might be mandatory to develop a more personalized postoperative rehabilitation program in poor-performing CI patients. The aim of the study was (1) to prove the hypothesis that linguistic difficulties in PP are key deficits which may explain the extremely poor speech perception in these subjects and (2) to discuss options of auditory training which might help to overcome these deficits.

Materials and Methods

Subjects

Seventeen adult CI users with a speech perception score between 45 and 65% in the Freiburg monosyllabic speech test [Hahlbrock, 1953] at 65 dB (AP) and 15 with a maximum speech perception of 30% (PPs) and 19 SP with a score more than 70% as previously described were included in the present study. Inclusion criteria were the following: at least 1 year of CI experience, no mental or neurocognitive disorder, full insertion of the electrode array, and normal functioning of electrodes. All subjects except 1 SP (mild) and 1 PP (moderate) had a severe hearing loss on the contralateral side, too, and all except one of each group did use hearing

Table 1. Profile of the subjects

	PP	AP	SP	p value PP-AP AP-SP	Cohen's *d* PP-AP AP-SP
Female	10	10	12	0.45	–0.28
Male	5	7	7	0.55	0.20
Age, yr					
Mean	71.60	68.00	66.95	0.21	0.46
(SD)	(8.10)	(7.49)	(10.96)	0.95	0.11
CI experience, yr					
Mean	4.87	4.18	6.0	0.58	0.23
(SD)	(3.14)	(2.79)	(4.84)	0.31	–0.46
Duration of deafness[1]					
Mean	3.00	2.53	2.21	0.4	0.29
(SD)	(1.65)	(1.51)	(1.18)	0.64	0.24
Years of education					
Mean	11.36	11.59	13.79	0.98	–0.12
(SD)	(1.55)	(2.29)	(2.67)	0.014*	–0.88
Freiburger monosyllabic test					
Mean, %	15	55	80	<0.000005***	–4.15
(SD)	(11.80)	(9.32)	(4.85)	<0.000005***	–3.96

[1] Duration of deafness was categorized as follows: <1 year = 1; 2–3 years = 2; 3–5 years = 3; 5–10 years = 4. * Indicates $p < 0.05$. *** Indicates $p < 0.001$.

aid or CI on the contralateral side. The performance groups did not differ with regard to age, duration of hearing loss before CI as well as CI experience, onset of hearing loss, and etiology. PP and AP had similar education periods whereas SP had significant higher educational level than AP (shown in Table 1).

Neurocognitive and linguistic skills were assessed by nonauditory test batteries: in the Lexical Decision Test [Carroll et al., 2016], subjects were shown letter combinations of existing and nonexisting words on the screen. By pressing a key, subjects were asked to decide whether the word was an existing or nonexisting word. Correctness of the answers and reaction speed for existing words, as an indication of the speed of lexical decision-making and word access, were measured.

In the Rapid Automatized Naming Test [Mayer, 2016], subjects correctly had to name objects as quickly as possible. Time was measured and number which could be named per second was determined.

The LEMO 2.0 (Subtest Internal Reading-Phonological Word or Neologism) [Stadie et al., 2013] was used to collect information about phonological input lexicon. In this test, subjects had to recognize whether a written (orthographically wrong) word sounds like a real existing word.

Furthermore, the Text Reception Test (TRT) [Zekveld et al., 2007] was carried out. In this test, written sentences were visually presented to the subject analogous to the German listening test OLSA (Oldenburger sentence test). Sentences were partially covered by periodic bars. Subjects had to read out as many parts of the sentence as possible. Thereby percentage of the text which could be covered in order to be able to recognize 50% correctly was determined.

The Reading Span Test (Oldenburger version, HörTech, version 1.1.2 [Carroll et al., 2015]) measures verbal working memory. In this test, the subject is asked to recognize meaningful and senseless sentences on the screen in a first task. In a second task, the subject has to remember the first or the last words of previously shown sentences.

The computer-based ALAcog assessment [Falkenstein et al., 1999; Völter et al., 2017] is a completely nonauditory neurocognitive test battery, where all tasks are explained in written instructions on the screen.

It consists of different subtests: The M3 measures the attention. If an M with 3 dots appears on the screen, the subject has to press a key; no reaction should be made in case of a distractor. The OSPAN assesses working memory. In this dual task, mathematical equations must be evaluated as correct or incorrect. In addition, a letter or number appears after each equation and has to be remembered and repeated. In the N-back task which consists of the 0- and the 2-back, subjects have to react if a presented letter is identical to the target letter (0-back) or the second last (2-back) presented letter. Inhibition is measured by the Flanker subtest (incompatible and compatible Flanker). The subject has to react to a target stimulus (left arrow/right arrow). Above and below the target stimulus, there are arrows pointing either in the same direction (compatible) or in the opposite direction (incompatible Flanker) or present as broken arrows (distractor). In the Verbal Fluency Test, subjects are asked to tell as many animals with a special initial letter as possible within a given time. Short and delayed memory are assessed by recall immediately and by delayed recall test after 30 min.

For each subtest, raw data including reaction time and number of correct and incorrect answers were assessed. Total performance, inverse efficiency (IE), was calculated based on the time needed and the number of correct answers given. A lower IE score indicates a better cognitive performance. Anamnestic data were obtained in a structured interview and from the patients' records.

Table 2. Results of the ALAcog subtests, the Reading Span Test, the TRT, the RAN, the Lexical Decision Test, and the LEMO 2.0 Subtest V9

Subtests	*N*	Mean	SD	*p* value PP-AP AP-SP	Cohen's *d* PP-AP AP-SP
ALAcog					
M3					
PP	15	1282.67	618.6		
AP	17	826.65	215.47	0.009**	1.01
SP	18	780.50	221.8	0.53	0.21
Recall					
PP	15	538.00	182.76		
AP	17	470.00	197.67	0.34	0.36
SP	18	416.11	219.66	0.43	0.26
Delayed recall					
PP	15	692.67	162.46		
AP	17	591.77	240.11	0.22	0.49
SP	18	511.67	234.38	0.37	0.34
N-back					
PP	14	419.57	532.40		
AP	17	282.77	275.54	0.32	0.33
SP	18	210.17	189.65	0.68	0.31
OSPAN					
PP	15	789.53	386.60		
AP	17	521.53	229.14	0.041*	0.86
SP	18	468.11	248.60	0.44	0.22
Flanker					
PP	15	139.53	142.45		
AP	17	142.29	75.94	0.35	−0.03
SP	18	102.89	80.89	0.15	0.50
Verbal fluency					
PP	15	817.00	87.03		
AP	17	757.06	113.15	0.084	0.59
SP	18	742.50	97.37	0.51	0.14
RST					
Task 1					
PP	13	43.39	9.54		
AP	16	49.12	4.14	0.023*	−0.82
SP	18	48.33	5.30	0.54	0.18
Task 2					
PP	13	17.69	4.91		
AP	16	24.00	7.30	0.015*	−0.99
SP	18	21.83	8.08	0.55	0.28
TRT					
PP	13	38.34	7.82		
AP	16	46.38	5.89	0.0024**	−1.18
SP	17	47.28	3.29	0.87	−0.19
RAN (items/s)					
PP	14	1.12	0.20		
AP	16	1.33	0.20	0.0026**	−1.01
SP	18	1.38	0.20	0.31	−0.26
Lexical Decision Test					
PP	14	1033.21	382.30		
AP	16	800.35	252.21	0.026*	0.73
SP	18	784.68	194.10	0.99	0.07
LEMO					
PP	15	66.13	9.00		
AP	16	74.50	3.20	0.0085**	−1.26
SP	19	74.63	4.62	0.43	−0.03

Lower scores of IE in ALAcog indicate better performance. Higher scores in the Reading Span Test and in TRT, RAN, and LEMO indicate better performance. In the Lexical Decision Test (reaction time), lower scores indicate better performance. Due to unexpected health problems in some subjects, a few subtests are missing. PP, poor performer; AP, average performer; SP, star performer. * Indicates $p < 0.05$. ** Indicates $p < 0.01$.

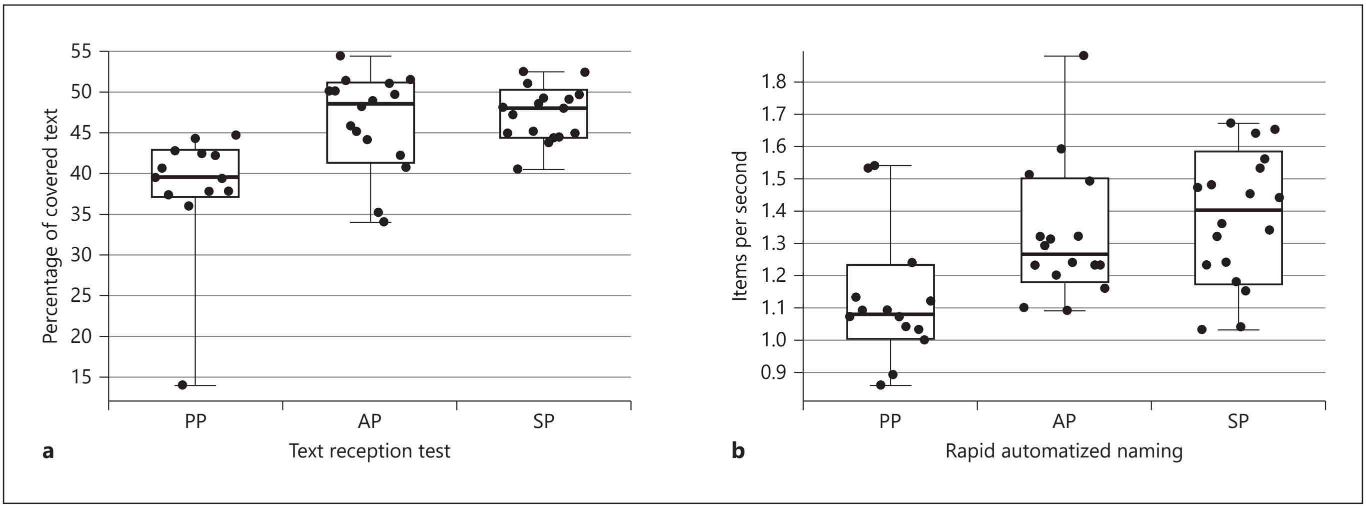

Fig. 1. a, **b** Boxplots of the results of the TRT and the RAN. Higher scores indicate better performance. PP, poor performer; AP, average performer; SP, star performer.

Statistics

Data of the linguistic and cognitive performance of AP were statistically compared to PP and SP [Völter et al., 2020a] by the Mann-Whitney-U-Test, a nonparametric statistical test for ordinal scaled data. Effect size was calculated with Cohen's *d*. To counteract the problem of multiple comparisons, the Holm-Bonferroni correction was applied and alpha level was set at 0.05 [Holm, 1979].

First, a discrimination analysis based on all subtests was done to rule out whether PP could be separated from AP. Afterward, a nonparametric discriminant function analysis according to Dirschedl with the two factors which represent the highest significant difference between AP and PP was carried out.

Results

Comparison between PP and AP

In the ALAcog, significant differences were found between PP and AP in the areas of attention and working memory (shown in Table 2): PP (IE = 1282.67) differed from AP (IE = 826.65; $p = 0.009$) on the M3 which measures the level of attention with regard to the total IE, but also concerning correctness ($p = 0.0056$) and response time ($p = 0.031$). AP also performed significantly better on the OSPAN than PP (IE = 521.53 vs. 789.53; $p = 0.041$). PP was significantly slower in completing mathematical equations than AP ($p = 0.038$). In the recall task, AP performed slightly better than PP (1.9 items vs. 2.4 items; $p = 0.3$). However, no significant difference was found. In the Verbal Fluency Test, no significant difference was observed between PP and AP (IE = 817.00 vs. 757.06, $p = 0.084$). However, although on average AP outperformed PP in all subtests, no significant differences between PP and AP were found in the ALAcog subtests of recall ($p = 0.34$), delayed recall ($p = 0.22$), inhibition (Flanker $p = 0.35$), and N-back ($p = 0.32$), as shown in Table 2.

Furthermore, a significant difference was observed between PP and AP in the Reading Span Test, which, like the OSPAN, assesses working memory by a dual task. PP performed significantly poorer than AP in both task 1 (decision if a sentence makes sense or not; $p = 0.023$) and task 2 (recall of the first/last words of a sentence; $p = 0.015$).

In the Text Reception Test, AP also performed significantly better ($p = 0.0024$); i.e., significantly more parts of a sentence could be covered in the AP group than in the PP group to obtain a readability rate of approx. 50% (as shown in Table 2; Fig. 1a).

In the Rapid Automatized Naming Test, AP were significantly faster; i.e., they were able to name more objects per second than PP ($p = 0.0026$) (as shown in Table 2; Fig. 1b).

In the Lexical Decision Test, PP were significantly slower in retrieving words than AP (1033 vs. 800 ms, $p = 0.026$). The most significant difference was found with high-frequency words ($p = 0.0055$). AP gave correct answers slightly more often (68 vs. 71 correct answers), but this difference was not significant ($p = 0.14$). In the LEMO for the assessment of the phonological input lexicon, AP gave significantly more correct answers than PP (74.5 vs. 66.13; $p = 0.0085$). Both with regard to neologisms ($p =$

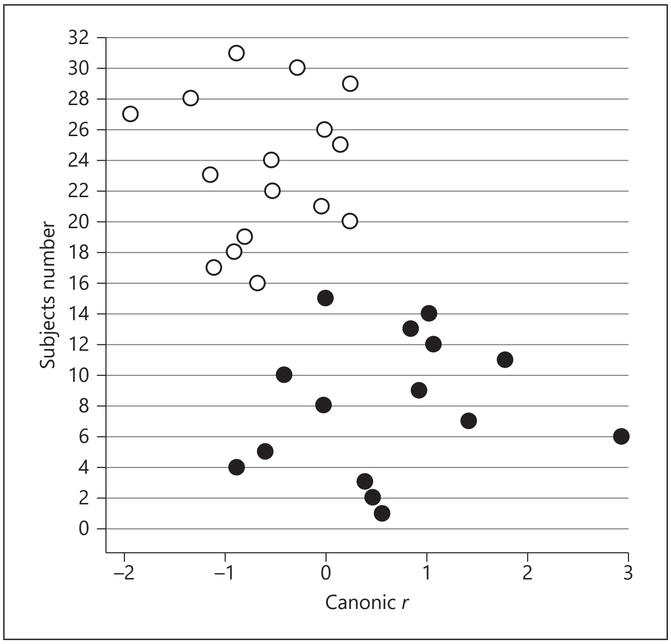

Fig. 2. Discrimination analysis of PP (black dots) and AP (white dots) based on the different subtests ($p = 0.028$, $r = 0.61$).

0.046) and words that sound like real words ($p = 0.045$), PP made significantly more mistakes than AP. After Holm-Bonferroni correction which required p values of less than 0.0037 and 0.0041, only the TRT ($p = 0.0024$) and the RAN test ($p = 0.0026$) met criteria for statistical significance.

This observation was underlined by a discrimination analysis which could clearly distinguish PP from AP ($p = 0.028$, $r = 0.61$) as shown in Figure 2. In the nonparametric discriminant analysis of Dirschedl based on the two factors with the highest scores (TRT and RAN), AP significantly differed from PP solely based on these two subtests ($p = 0.0000001$). If TRT was higher than 44.65, it was an AP subject in 100%. If TRT was equal or lower than 44.65 and the RAN task was added to the TRT outcome as the second parameter, also a 100% distinction between the two groups could be done if the items per second were equal to or lower than 1.13 (shown in Table 3).

Table 3. Results of the nonparametric discriminant function analysis according to Dirschedl

	Total	PP	%	AP	%
TRT ≤ 44.65					
RAN ≤ 1.13	11	11	100.00	0	0.00
RAN > 1.13	7	2	28.57	5	71.43
TRT > 44.65	11	0	0.00	11	100.00

Comparison between AP and SP

Performance of AP did not significantly differ from the performance of SP on any of the ALAcog subtests ($p = 0.15–0.68$). Besides, no significant differences were found neither in the Reading Span Test, the Text Reception Test, nor any other of the linguistic tests ($p = 0.31–0.99$) as shown in Table 2. This was also true for the discrimination analysis which could not find a difference between AP and SP ($p = 0.63$, $r = 0.55$).

Comparison between PP and SP

Significant differences between the PP and the SP were detected most prominent in attention ($p = 0.003$), but also in working memory (OSPAN [$p = 0.0068$]), delayed recall ($p = 0.04$), and inhibitory control ($p = 0.037$). Furthermore, SP outperformed PP in phonological input lexicon and word retrieval assessed by the LEMO ($p = 0.0039$) and SP were faster in lexical access in the Lexical Decision Test ($p = 0.017$) and the RAN ($p = 0.0026$). For a more detailed description, see Völter et al. [2020a].

Discussion

The present results show that PPs' linguistic and cognitive abilities do not only differ from SP (as reported in Völter et al. [2020a]) but also from AP, i.e., from the major group of CI users with medium speech perception [Boisvert et al., 2020; Carlson, 2020; Dazert et al., 2020]. In contrast, AP do not differ from SP in any of the domains investigated in this study. This suggests that PP probably represents a distinct entity in CI users not only in terms of speech perception but also with regard to linguistic and cognitive properties.

Major differences between PP and AP performance groups were found in phonological processing. Phonological skills and refined phonological representations play an important role in a large number of cognitive processes such as spelling, reading, and learning new vocabulary. They are closely connected to the phonological storage and to a fast access to words. Phonological processes include (1) phonologic awareness as the listeners' abilities to recognize detailed phonological structure in the speech stream, (2) long-term phonological representations, and (3) word retrieval [Lee et al., 2012]. As previous studies have described, phonologic processes may change with age but also due to long-term hearing loss [Rönnberg et al., 2013].

To solve a phonological task, different ways to process speech have been described in functional MRI studies [Lazard et al., 2010; Lazard and Giraud, 2017]. Whereas good performers as well as normal hearing subjects mainly activated the left lateralized dorsal phonological route when performing a visual rhyme judgment task, a ventral temporo-frontal route and right supramarginal gyrus have been used by CI users with poor speech outcome [Lazard and Giraud, 2017]. This might explain why rapid naming on the RAN and phonological input on the LEMO were significantly more difficult for PP than for AP. PP also had poorer results on the TRT which correlates with performance in speech perception in noise and requires performance in word retrieval in lexical decision-making [Zekveld et al., 2018].

Considerable differences between the two performance groups of PP and AP were also observed in the domain of verbal fluency; however, the differences were not significant, may be due to the limited sample size. It also needs to be taken into consideration that the Verbal Fluency Test used in the present study consists of a combination of categorical and semantic settings and does not only cover word retrieval. Whereas phonemic fluency (generation of words beginning with a certain letter) can mainly be explained by phonological processing difficulties, semantic category fluency (generation of words belonging to a certain semantic category) mainly relies on executive control such as inhibitory skills assessed by the Flanker task which was similar in both groups of our study sample.

Furthermore, significant differences were also found in the phonological input lexicon. E.g., PP by mistake rated phonological neologisms as existing words more often than the average performance group did. The underlying reason is unknown. Long-lasting postlingual hearing loss is supposed to lead to degradation of the phonological representations in long-term memory which need to be continuously activated and regularly trained by optimal auditory perception [Rönnberg et al., 2011]. PP seem considerably more affected hereby than CI users with better speech perception performance. However, one might also speculate that phonological deficits exist in PP subjects independently of the hearing impairment. This fits to data recently published by Esbensen and Thomson [2020]. Only children with hearing loss and language difficulties showed significant word retrieval or lexical organization difficulties whereby hearing impaired children without did not [Esbensen and Thomsen, 2020].

Besides linguistic domains, PP also considerably differed from AP in the domain of attention and in verbal working memory which strongly relies on attention. This did not only become obvious on the dual task in OSPAN which is mainly targeted to nonverbal memory retention but also on the verbal working-memory-related RST task in which subjects had to assess the meaningfulness of a sentence. In this task, working memory, word retrieval, and phonological retention depend on each other. In contrast, there was no significant difference in the N-back which seems to assess a different area of working memory as reported in earlier studies who could not find any correlation between the OSPAN and the N-back task either [Kane et al., 2007; Jaeggi et al., 2010].

For retrieving words semantically and phonologically, similar representations are activated in the brain. If the activation is equal or higher for a word other than the target word, conflict arises which has to be solved by cognitive control. This might lead to the tip-of-the-tongue phenomenon, slowed recall, and word-finding problems [Ladányi and Lukács, 2019]. Interestingly, almost all subjects who had difficulties with retrieving words also had cognitive deficits measured by the M3 and the OSPAN. Mostly, the phonological input storage was also affected. This fits to the observation that in some children with language impairment both working memory and word retrieval were affected [Ladányi and Lukács, 2019].

However, as CI users have to apply slow and effortful processing mechanisms to compensate for poor fast automatic processing of language as described by RAMBPHO (Rapid, Automatic, Multimodal Binding of Phonology) in the Ease of Language Understanding Model [Rönnberg et al., 2019, 2021; Smith et al., 2019], working-memory capacity is reduced, especially in case of insufficient auditory input. The consequence is that the subject lacks cognitive reserves for the fulfillment of other tasks and that therefore the performance on dual tasks like on the OSPAN or on the RST is poorer. Further on, working memory is not only related to the post-dictional processing of speech but also to the ability to use information predictively to perceive speech, especially under more adverse auditory situations [Federmeier, 2007]. At very early levels of the auditory system, prediction affects stream segregation and the formation of auditory objects in RAMBPHO. In case the signal is degraded, such as in CI users, prediction and input in RAMBPHO is diminished [Zekveld et al., 2011; Zekveld et al., 2012; Hunter and Pisoni, 2018].

Besides working memory, verbal fluency is supposed to moderate the extent to which predictive processing is used [Federmeier et al., 2010; DeLong et al., 2012]. Studies have shown that older adults who are able to rapidly generate lexical items on demand can take advantage of these abilities during language processing to pre-activate the likely candidates for upcoming items. Therefore, the described difference in the verbal fluency performance between PP and AP might have an additional impact on speech perception.

No significant difference was found between PP and AP in the domain of memory performance, measured by the Recall and Delayed Recall tasks. This is also in accordance with our previous study [Völter et al., 2020a]; although differences were observed in memory between PP and SP, those were less pronounced than in other areas. As the entire test battery was presented in a nonauditory manner and no auditory speech understanding was required to fulfill the tasks successfully, the presented results indicate that PP is not only affected by impaired hearing but also by domain-general nonauditory abilities that might regulate speech processing.

One limitation of the present study is that we cannot be certain if the limited cognitive and linguistic abilities of PP are constitutional or if they are a consequence of long-term hearing loss. Lyxell et al. [1998] and Classon et al. [2013] ascertained that the phonological abilities measured by rhyme tasks negatively correlated with the duration of hearing loss whereas working memory was not affected [Lyxell et al., 2003]. Our study did not reveal a statistical difference with regard to the duration of hearing impairment.

Based on our results, the group of the low-performing CI users is an entity of its own which might benefit from a specific rehabilitation program specifically adapted to the cognitive and linguistic deficits of these subjects. It is well known that auditory training is necessary after cochlear implantation to adapt the brain to the new signal and thus to maximize the benefit [Fu and Galvin, 2008; Reis et al., 2019]. So far, auditory training in adult CI recipients has followed a standard regimen mainly focused on bottom-up processes and based on electrode discrimination training, targeted phonetic contrast training, speech-in-noise or telephone training, adapted to CI users with good, but not to those with a poor speech perception. In the presented study, deficits defected in PP mainly affected phonological representation, word retrieval, lexical access, as well as attention and working memory. These elements have not been covered by standard auditory training for adult CI users so far.

In order to strengthen a lexico-semantic strategy during word processing, targeted phonological training should be included [Moberly et al., 2017; Rudner et al., 2019] as this is the case in children suffering from dyslexia [Schneider et al., 2000; Glück, 2003; Siegmüller, 2008; Gilliver et al., 2016]. Significant positive effects on improved phonological processing have been reported after a 4-week training of computer-assisted phoneme-grapheme correspondence in 32 children with hearing impairment [Nakeva von Mentzer et al., 2013], especially in those severely impaired. This points out that not only an auditory, but also a written language training can have a positive effect on phonological skills. Therefore – although development of phonological abilities differs between children and adults – phonological training supported by written language might also be offered to poor-performing adult CI users to make phonology more accessible to them and to bypass their limited auditory speech perception.

Furthermore, our data point out that word retrieval is particularly slow in poor-performing CI users. Training of word retrieval by using phonological cues might help to fasten lexical access and improve phonological representations as shown in aphasia training. Henry et al. [2019] developed a 7-step hierarchy training program consisting of semantic, orthographic, and phonemic self-cues and clearly demonstrated in 18 subjects with primary progressive aphasia that training of word retrieval by using semantical and phonological cues is efficient in naming trained and untrained items up to 6 months after intervention. Meteyard and Bose [2018] underlined this observation but stressed that phonological cues are more effective than semantic cues in improving naming accuracy for aphasia patients.

Moreover, training of neurocognitive skills should be highly emphasized in auditory rehabilitation in PP. Benefits from verbal working-memory training even 6 months after the end of the training have already been found in pediatric CI users [Kronenberger et al., 2011]. Different kinds of video-game-like exercises which require auditory, visuospatial, short-term, and working-memory skills were offered 5 times a week for a period of 5 weeks. Recently, Payne and Stine-Morrow [2017] used a home-based cognitive computer-based training of verbal memory in 41 normal-hearing subjects and thus improved performance in both trained and untrained verbal memory tasks and in selective tasks of sentence memory, verbal fluency, and comprehension of syntactically ambiguous sentences. In contrast, Reis et al. [2021] could only show improvement in trained items, especially in the first training weeks, but no generalization on outcome measures beyond the training after a visual and auditory computer-based training in 26 experienced CI users.

The transfer of trained to untrained material is a key issue in rehabilitation in general [Shipstead et al., 2012; Henshaw and Ferguson, 2013; Melby-Lervåg and Hulme, 2013; Saunders et al., 2016]. In most studies dealing with auditory training, the impact on trained items has been described, but long-term or transfer effects have rarely been reported [Sweetow and Palmer, 2005; Bernstein et al., 2012; Ingvalson and Wong, 2013; Shafiro et al., 2015; Schumann et al., 2016; Green et al., 2019]. These mixed findings may be due to a limited overlap between the training and the untrained tasks, or due to an insufficient duration of the training used [Reis et al., 2021]. However, a combined auditory-cognitive program might have the potential to improve auditory and cognitive skills in CI users as shown in unaided hard-of-hearing adults [Anderson et al., 2013] and in hearing aid users [Sweetow and Sabes, 2006; Ferguson and Henshaw, 2015]. Another approach might be to include indexical information, which provide benefits in speech processing and generalization effects as proposed by Loebach et al. [2008].

In general, high intensity of the training schedule seems to be essential as shown in aphasia. An intense training of at least 10 h per week for a period of 3 weeks significantly improved verbal communication, even in severely affected patients suffering from chronical aphasia for at least 6 months [Breitenstein et al., 2017]. Besides, engagement of external and internal motivation of the user is mandatory for the success of the training [Henshaw et al., 2015; Völter et al., 2020b]. Computer-based training platforms based on modern learning concepts might be a promising way to train with high frequency and fun, independently of time and place [Tuz et al., 2021; Völter et al., 2021a].

Furthermore, training regimens adapted to the individual needs of the CI user should start off immediately after audio processor activation and not only when auditory training has remained unsuccessful for a longer period of time, in order to stimulate the plasticity of the brain as much as possible [Fraysse and James, 2020]. Unfortunately, to date, there is still a lack of standardized diagnostic and therapeutic material for hearing-impaired adults. Therefore, speech materials from aphasia therapy in adults or from speech and language therapy in children need to be adapted to adults with hearing impairment in the future.

Conclusions

Taken together, although the presented data need to be backed up with more research, the results support the view that CI users apply different strategies during sentence processing dependent on auditory and cognitive abilities [Kurthen et al., 2020]. PP do not only clearly differ from SP but also from AP with regard to cognitive and linguistic abilities and therefore seem to represent a separate entity. The domain mainly affected is phonological word retrieval, either due to the access to the lexicon or the limited phonological storage (encoding), combined with a reduced working-memory capacity.

Preoperative evaluation of the cognitive and linguistic skills might help to better predict speech perception after cochlear implantation. Moreover, these weaknesses in language processing may serve as targets for novel interventions for CI users who experience inferior spoken language outcome following cochlear implantation. Therefore, future work should investigate the relation between the adoption of a lexico-semantic strategy during phonological processing tasks and speech perception.

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Statement of Ethics

The study was in line with the World Medical Association Declaration of Helsinki. This study protocol was reviewed and approved by the ethic institution of the Ruhr-University-Bochum, approval number [No. 17–6025_6-BR]. All participants signed their informed consent.

Conflict of Interest Statement

The Department of Otorhinolaryngology, Head and Neck Surgery at the Katholisches Klinikum in Bochum, Ruhr-University of Bochum, has received third-party funds from MED-EL. C.V., J.P.T., and S.D. have received travel expense support from MED-EL.

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Author Contributions

Christiane Völter and Jan Peter Thomas designed the study. Kirsten Oberländer selected the subjects and collected data. Rebecca Carroll and Imme Haubitz analyzed and evaluated the data. Christiane Völter, Kirsten Oberländer, and Jan Peter Thomas wrote the manuscript with contributions and critical feedback from all authors. Stefan Dazert supervised the project.

Data Availability Statement

All data generated or analyzed during this study are included in this article. Further inquiries can be directed to the corresponding author.

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