1 **Postoperative Predictors of Speech Reception in Cochlear Implant**

2 **Users**

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1 **Abstract**

2 In general, cochlear implant users see considerable benefit from their implant. Yet, there is great
3 individual variation in speech reception. This study investigated whether individual differences in
4 auditory and visual working memory abilities are related to speech reception in noise. To this end,
5 we administered two tests of working memory – the WAIS-III Digit Span and PyVDT, a visual
6 monitoring task – to 25 cochlear implant users. We found duration of profound hearing loss and age
7 at profound hearing loss to be the best predictors of speech reception. We did not find Digit Span
8 scores or visual monitoring as measured by the PyVDT to be useful predictors of speech reception.
9 Additionally, we compared the Digit Span scores of our sample of cochlear implant users to the
10 Danish WAIS-III Digit Span normative sample. On the Digit Span Forward, cochlear implant users
11 scored approximately one digit lower than the normative mean; on the Digit Span Backward,
12 cochlear implant users scored approximately half a digit lower than the normative mean. The study
13 found no support for the ideas that auditory or visual working memory predicts speech reception.
14 Our results instead indicate that shorter durations of hearing loss predict good speech reception
15 outcomes, and vice versa.

16 **Introduction**

17 The cochlear implant – an electrode surgically inserted into the inner ear – holds the promise of
18 restoring the sense of hearing to profoundly hearing impaired individuals. Yet, there is great
19 individual variation in outcomes – some implantees benefit greatly, while others see only limited
20 results. This raises the question of whether individual differences in cognitive abilities might be
21 related to outcomes. This study attempts to answer this question by quantifying and modeling the
22 relationships, if any, between auditory and visual working memory abilities on the one hand, and

1 comprehension of speech in noise on the other. Put another way, we seek to determine if implantees
2 with longer working memory spans are better at discerning speech in noisy conditions than are
3 implantees with shorter spans. A related question concerns how the working memory span of
4 implantees compare to that of the population as a whole. In order to illuminate these issues, we
5 administered two tests alleged to measure working memory (one auditory; one visual) as well as a
6 speech reception test to a group of cochlear implant users.

7 **Cochlear implants and background noise**

8 The challenges presented by noisy environments to cochlear implant users have been described in
9 several studies. In a questionnaire study of 36 cochlear implant users, Lassaletta et al. [1] found a
10 high degree of satisfaction with the implant, except in noisy situations. Under these circumstances,
11 implant recipients reported only moderate satisfaction. Faber and Grøntved [2] reported a similar
12 pattern of results: implantees were generally satisfatied with their implant, except in noisy
13 conditions.

14 Because of the associated difficulties, one might expect implantees to avoid noisy situations.
15 Some studies have suggested that this might indeed be the case. Karinen et al. [3] found that social
16 isolation was more common in implant users than in the normal population. Similarly, Knutson et
17 al. [4, p879] found that cochlear implant users, although reporting a reduction in loneliness, still
18 experienced “considerable loneliness” 18 months after implantation.

19 **Cognitive abilities as predictors of speech reception**

20 **Auditory working memory**

21 The concept of working memory was introduced by Miller, Galanter, and Pribram [5] and
22 subsequently expanded by Baddeley and Hitch [6]. Miller et al. [5] conceptualized working

1 memory as an ability supporting the realization of "Plans" which in turn are defined as descriptions
2 of an organism's behavior and considered "essentially the same as a program for a computer" [5,
3 p16]. Later theorizing (see [7] for a review) has retained this computer metaphor. This is evident,
4 for example, in Baddeley's (e.g., [8]) multicomponent model of working memory and the associated
5 ideas of storage, maintenance, and manipulation of information.

6 The concept of working memory has been successful in its capacity to account for
7 experimental findings – although many of these are of a fairly artificial nature with limited
8 ecological validity – and prompt new research questions [9]. Tests of working memory such as the
9 digit span (e.g., [10]) and the reading span [11] have proved pragmatically useful in that these tests
10 reliably correlate with a range of cognitive abilities [7].

11 The association of cognitive abilities with working memory also appears to hold for speech
12 reception. Indeed, after reviewing 11 studies investigating the association between working memory
13 spans (e.g., digit span and reading span) and speech reception, Akeroyd [12, pS66] concluded that
14 tests of working memory "mostly" correlate with speech reception. Of the four studies that tested
15 digit spans specifically, two reported statistically significant associations with speech reception [12,
16 pS61].

17 Baddeley's model of working memory posits a number of constructs: the visuospatial
18 sketchpad, the central executive, the episodic buffer, and the phonological loop. An important
19 question regarding the implied association between working memory and speech reception in
20 cochlear implant users, therefore, is whether this association is specifically related to the
21 phonological loop, i.e. the auditory component of the model. The WAIS-III Digit Span, included
22 among the tests administered in this study, is thought to be a measure of working memory capacity.

23 In a study investigating working memory in cochlear implanted children, Pisoni and Cleary
24 [13] suggested that around seven percent of the variance in word recognition scores could be

1 explained by working memory ability. Similarly, in a study of 43 cochlear implanted children aged
2 eight to nine, Pisoni and Geers [14] found medium to large correlations between digit span and
3 speech reception measures. Pisoni and Geers [15, p. 3] hypothesized that their findings "may reflect
4 fundamental differences in the speed and efficiency of elementary information processing
5 operations that are used in the encoding, rehearsal, retrieval, and manipulation of the phonological
6 representations of spoken words." In a follow-up study of 22 cochlear implanted children aged eight
7 to nine, Cleary, Pisoni, and Geers [14] replicated this finding; they found a statistically significant
8 medium-sized correlation between digit span and speech reception.

9 **Visual monitoring tasks**

10 Some studies (e.g., [16–18]) have suggested that auditory deprivation might lead to enhanced visual
11 perception. In light of these findings, it is interesting that others (see [12] for a review) have found
12 that the ability to successfully perform certain visual tasks is associated with good speech reception.
13 Specifically, two related tests have been employed in previous studies: the Visual Monitoring Task
14 (VMT) [4] and visual letter monitoring [19]. The VMT displays single digits, one at a time, on a
15 computer monitor, and participants are instructed to press a key whenever an "even-odd-even"
16 pattern of digits is displayed. The visual letter monitoring task [19] displays single letters instead of
17 digits, but is otherwise identical to the VMT. Knutson et al. [4, p820] found VMT scores to account
18 for around one tenth to one quarter of the variance in speech reception in a study of 29 cochlear
19 implant users. This led Knutson et al. [4, p821] to conclude that "cross-modality predictions can be
20 made", i.e. that a visual measure – the VMT – can predict a skill in a different modality, i.e. hearing
21 via a cochlear implant.

22 In a review of five studies using Gatehouse's [19] letter monitoring task, however, Akeroyd
23 [12] found mixed results regarding its association with speech reception. Akeroyd's [12, pS66]
24 evaluations of these studies range from "some success" to "notable success", with one reviewed

1 study “[failing] to obtain any significant effects with [the letter-monitoring task]”. It is worth
2 noting, however, that the latter study [20] was later retracted due to coding errors relating to
3 unspecified results and conclusions [21]. It is unclear whether these errors also invalidate the
4 conclusions drawn regarding the letter monitoring task used.

5 In his review of the relationship between cognitive abilities and speech reception in noise,
6 Akeroyd [12, pS65] concluded that the twenty studies he reviewed “clearly [demonstrate] that there
7 is a link between cognition and speech reception in noise”. Akeroyd went on to qualify this,
8 however, by stating that “[cognition] offers only a secondary effect, as hearing loss remains the
9 primary predictor of speech reception”. It is important to note, however, that Akeroyd did not look
10 at cochlear implantees specifically, so his conclusions do not necessarily generalize to this group.

11 There is some disagreement regarding what the VMT measures. Akeroyd [12, pS58]
12 describes the VMT “as incorporating attention, reaction time, continuous performance, and working
13 memory”, but misattributes this description to Gatehouse et al. [19, 22, 23] who do not appear to
14 provide this description of the VMT in the articles cited by Akeroyd. Nevertheless, Akeroyd's
15 description of the VMT is in agreement with Gfeller et al. [24, p392] who consider the VMT “a test
16 of attention, reaction time, and working memory”. Also, the description is in partial agreement with
17 Gfeller et al. [25, p6] who claim that the VMT “requires participants to correctly identify sequential
18 information” and “requires rapid responding and working visual memory [sic]”. Knutson, the author
19 of the VMT [4, p819] claims that the VMT requires participants to maintain and update digits in
20 working memory. In later work, Knutson claims that the VMT “does include a memory component”
21 [26, p154] and that there is a “probable importance of working memory in the VMT” [26, p156].

22 **The present research**

23 The current study has two main aims. First, we intend to quantify the working memory span of our

1 sample of cochlear implant users by comparing their WAIS-III Digit Span [10,27] scores to those of
2 the Danish WAIS-III normative sample. Second, we intend to determine if cognitive abilities
3 (operationalized as performance on the Digit Span and the VMT tests), demographic factors, and/or
4 information relating to the participants' hearing impairment (see Table 1) can be used as predictors
5 of speech reception scores. An additional aim is to test the feasibility of our newly developed
6 reimplementation of the VMT, called PyVDT (described below). Lastly, with potentially invalid
7 results published by Rudner et al. [20,21], we aimed to reexamine the relationship between
8 monitoring tasks and speech reception.

9 **Methods**

10 **Participants**

11 Twenty-five unilaterally implanted cochlear implant users (18 female), all native Danes,
12 participated in the study. All participants had received their implant at the Department of
13 Otorhinolaryngology, Head and Neck Surgery, Aarhus University Hospital, Denmark. In all 25 cases,
14 surgery was performed by two highly experienced surgeons, of which one is the third author of this
15 study. The participants were a subset of a larger sample of 163 respondents who had participated in
16 a previous questionnaire study. In this questionnaire study, we asked participants to indicate in
17 writing whether or not they would be interested in participating in additional studies. Of the
18 respondents who had expressed willingness to participate in such studies, we invited those who
19 were unilaterally implanted and postlingually hearing impaired to participate in the present study.
20 The etiologies of these 25 participants in regards to hearing loss were as follows: meningitis (two
21 cases), congenital causes (two cases), genetic causes (two cases), and unknown causes (18 cases).
22 For additional information on the participants, see Table 1.

Research ethics

In accordance with the Helsinki Declaration, we submitted a thorough description of the present study to The Central Denmark Region Committees on Health Research Ethics. The Committees found that the study did not require formal approval due to its descriptive nature. Nevertheless, all participants received extensive written information about the study and their rights as participants. Prior to the present study, we obtained written consent from all participants who confirmed their willingness to participate.

Table 1: Demographic and clinical data

Participant	Gender	Age	Years of profound hearing loss	CI experience (years)	Side of implant	Implant vendor
1	F	55	48	4	Left	Cochlear (Nucleus)
2	M	60	49	6	Left	Cochlear (Nucleus)
3	F	50	17	3	Left	Cochlear (Nucleus)
4	M	32	28	1	Right	Cochlear (Nucleus)
5	F	64	22	3	Right	Cochlear (Nucleus)
6	F	58	36	0	Right	Cochlear (Nucleus)
7	M	56	43	2	Left	Cochlear (Nucleus)
8	F	64	28	0	Left	Cochlear (Nucleus)
9	M	55	49	6	Right	Cochlear (Nucleus)
10	F	43	22	1	Right	Cochlear (Nucleus)
11	F	37	25	6	Right	Cochlear (Nucleus)
12	F	35	15	1	Right	Cochlear (Nucleus)
13	M	58	48	2	Right	Cochlear (Nucleus)
14	M	55	54	2	Left	Cochlear (Nucleus)
15	F	51	31	10	Right	Cochlear (Nucleus)
16	F	39	22	7	Right	Cochlear (Nucleus)
17	F	66	Unknown	1	Right	Cochlear (Nucleus)
18	F	62	11	6	Right	Cochlear (Nucleus)
19	F	47	5	1	Right	Advanced Bionics
20	F	56	23	1	Right	Advanced Bionics
21	F	60	46	8	Right	Cochlear (Nucleus)
22	M	64	17	7	Left	Cochlear (Nucleus)
23	F	52	Unknown	8	Left	Cochlear (Nucleus)
24	F	58	19	9	Left	Cochlear (Nucleus)
25	F	44	25	5	Left	Cochlear (Nucleus)
Mean		52.8	29.7	4		
Range		32 – 66	5 – 54	0 – 10		

Please note: age at profound hearing loss and age at implananation are not included in this table. These variables are available as part of the supplementary material accompanying this article (S2 Dataset).

Apparatus

The laptop used to administer the PyVDT (our reimplementation of the VMT; described below) was

1 a 13” MacBook Pro with the model identifier “MacBookPro5,5”. Participants used the space bar on
2 the built-in keyboard to indicate detection of the target (even-odd-even) pattern of digits.

3 The DANTALE II test [28] (described below) was administered in an acoustically treated
4 room. Participants responded by tapping on a touchscreen displaying a closed set of possible words
5 (10 alternatives per word per trial; see [28] for further details on the testing procedure).

6 **Procedure**

7 Testing took place at the West Danish Cochlear Implant Centre, Department of
8 Otorhinolaryngology, Head and Neck Surgery, Aarhus University Hospital. Each participant
9 completed the cognitive tests (specifically, the Digit Span and the PyVDT) in a one-to-one session
10 with the first author who . The WAIS-III Digit Span and PyVDT were administered in a quiet room.
11 Technical staff at Aarhus University Hospital administered the DANTALE II speech-in-noise test.
12 Prior to testing, participants filled out a questionnaire covering demographics, etiology and duration
13 of hearing loss, and implant information (see Table 1).

14 **Digit Span**

15 We administered the Digit Span according to the Danish WAIS-III Manual [10] and as described in
16 an earlier study [29]. Participants were seated in a quiet room and facing the first author, so that
17 they were able to lip read if desired.

18 **PyVDT: a visual monitoring task**

19 We instructed participants to press the spacebar on the laptop whenever the target sequence of digits
20 (see below) was shown on the laptop monitor during the PyVDT. The experimenter left the room
21 during testing in order to minimize distractions.

22 During the VMT [4], single digits are shown one at a time on a laptop monitor. Participants

1 are instructed to press the space bar on the laptop keyboard whenever the most recently displayed
2 digits match the target sequence, an even-odd-even pattern of digits. The VMT contains two
3 difficulty levels, designated "VMT-1" and "VMT-2" [4]. During the faster VMT-1 subtest, digits
4 change every second; during the slower VMT-2 subtest, digits change every two seconds.

5 PyVDT displays the digits one through eight exclusively, and all participants were shown
6 the same two pseudo-random digit sequences (one sequence during the faster subtask which
7 displays one digit every second; one during the slower subtask which displays one digit every two
8 seconds). Since the VMT [4] was not available to us, we created the highly similar PyVDT using
9 PsychoPy [30,31], a stimulus presentation application based on the Python programming language
10 [32]. We consulted the original author of the VMT (John F. Knutson, University of Iowa) as well as
11 previous studies using the VMT [4,24,25] in order to ensure an accurate recreation of the test.

12 **DANTALE II: sentences in noise**

13 All participants completed the DANTALE II test [28], a Danish adaptation of the Swedish language
14 Hagerman sentence test [33]. The DANTALE II test is an adaptive method for assessing the speech
15 reception threshold (SRT) of participants. During the test, background noise and five-word spoken
16 sentences of the form "name – verb – numeral – adjective – object" (e.g., "Linda owns eight white
17 boxes") are played on a set of speakers. The noise volume is increased or decreased in an adaptive
18 fashion based on the participant's responses until their SRT has been determined. The SRT is
19 defined as the ratio between speech and noise where a maximum of two words in a five-word
20 sentence can be correctly identified.

21 Wagener et al. [28] reported a mean SRT for 60 normal hearing subjects, all native Danes, of
22 -8.43 dB. The normal hearing threshold thus indicates that participants were able to identify words
23 under conditions where speech was 8.43 dB quieter than the noise. In comparison, Hagerman and
24 Kinnefors [33] reported a mean SRT for 10 normal hearing subjects of -7.8 dB.

1 Results

2 Analytical approach

3 The problems with null hypothesis significance testing (NHST) – for example, faulty logic and
4 dichotomous decision-making – have been known for decades (e.g., [34–37]), but the field of
5 psychology only recently begun reducing its reliance on this approach. The American Psychological
6 Association [38, p33] states that NHST by itself is insufficient when reporting results. Instead, the
7 APA [38, p34] consider confidence intervals "the best reporting strategy" and strongly recommends
8 using them. Similarly, the problems with NHST have prompted the journal Psychological Science
9 [39, pp5–6] to recommend that authors instead use "the new statistics" [40], an approach which
10 relies on estimation techniques including effect sizes, confidence intervals, and meta-analysis. We
11 acknowledge that NHST is flawed, and consequently, our approach to the statistical analyses
12 follows the recommendations given by Cumming [40,41]. We do not report p values since statistical
13 significance can be inferred from confidence intervals (which we do report), and since p values
14 have been shown to mislead (e.g., [41]).

15 We performed the statistical analyses using R [42] as well as the Rcmdr [43] and WRS [44]
16 R packages.

17 In general, sample means and sample standard deviations are not robust; that is, these
18 measures are highly affected by relatively small changes in the distributions which the measures
19 describe [45]. Thus, there is a risk that these measures might lead to inaccurate results. For this
20 reason, we used robust measures to analyze our data. Specifically, we used 20% trimmed means,
21 bootstrapped confidence intervals, and robust regression [45,46].

22 Our decision to use 20% trimmed means is based on Wilcox's [45] recommendations.
23 Wilcox's [45, p55] view is that 20% trimmed means are "a good choice for general use" and that

1 they "[guard] against complete disaster but [sacrifice] relatively little").

2 For our regression analyses, we used the Theil-Sen estimator since it is robust to outliers and
3 since accurate confidence intervals can be computed for this estimator under conditions of
4 nonnormality and heteroscedasticity [46, p208]. A disadvantage of the Theil-Sen estimator,
5 however, is that its robustness to outliers decreases as the number of predictors increases [46, p224].
6 Consequently, in order to avoid creating a misleading model containing multiple predictors, we
7 chose to perform separate simple regression analyses for each of the predictors (see Table 1 for a list
8 of predictors). Further, simulation studies (e.g., [47]) have found the Theil-Sen estimator to perform
9 well compared to ordinary least squares regression when sample sizes are low (as is the case here).
10 We believe this analysis strategy constitutes the best compromise and provides the best estimates
11 given that the usual assumptions for parametric methods are not met by our data.

12 Regarding the multiple comparisons problem, Cumming [41, p422] acknowledges that "[in]
13 the estimation world, there's no well-established [confidence interval] adjustment comparable to the
14 Bonferroni correction". Cumming's [41, p422] view is that researchers should instead "rely on
15 careful judgment than on an arbitrary numerical adjustment".

16 When computing 95% confidence intervals for the intercept and the slope of the linear
17 models, we followed Wilcox [46] recommendation of using a bootstrap size of 599 which "gives
18 good results for a wide range of situations" [46, p209]. Wilcox [46, p208] explains that confidence
19 intervals for the slope and the intercept should be calculated using a percentile bootstrap robust to
20 heteroscedasticity, so we used Wilcox and Schönbrodt's [44] "regciMC" R function, a robust
21 percentile bootstrap function, to estimate these two confidence intervals. We calculated coefficients
22 of determination using Wilcox and Schönbrodt's [44] "tsreg" R function.

23 As for the Digit Span, we report the number of digits correctly remembered (i.e., longest
24 spans), not raw scores (i.e., the number of correct trials). To enable comparisons between the mean

1 spans of the cochlear implant group and those of the normative sample, we calculated 95%
2 confidence intervals for the mean spans and the mean differences. We used the 20% trimmed mean
3 of the cochlear implant group and the regular sample standard deviation of the cochlear implant
4 group in our estimation of the mean between-group Digit Span differences. We used Cumming's
5 [41, p156] formula 6.2 to calculate the confidence interval for the mean differences.

6 To facilitate comparisons between our PyVDT results and the VMT results reported by
7 Gfeller et al. [25], we report A' [48], a non-parametric estimate of sensitivity (i.e., the ability to
8 distinguish between stimuli; [49, p3] for each participant's PyVDT score. Like Gfeller et al. [25,
9 p7], we calculated A' according to the formula provided by Gescheider [50, p145].

10 **Missing data and data quality**

11 We obtained complete and valid Digit Span Forward and Backward data for all 25 participants.

12 Three participants' PyVDT results were excluded from the analysis due to a technical error
13 with the test, due to noncompliance (as evidenced in the log file by constant pressing of the
14 spacebar), and due to misunderstanding the instructions (as evidenced by a very high false alarm
15 rate), respectively. Additionally, the slower PyVDT subtask proved too easy for our participants,
16 with 19 out of 22 participants obtaining an A' greater than .95 (i.e., almost at ceiling; $n=22$; mean
17 $A'=.96$; range: .60–1). Consequently, we did not include the slower PyVDT subtask data in the
18 regression analyses. Scores on the faster PyVDT subtask were not at ceiling ($n=22$; mean $A'=.90$;
19 range: .79–.99).

20 Due to technical errors, DANTALE II speech reception scores were unavailable for three
21 participants. Consequently, we obtained valid DANTALE II scores from 22 participants. Of these
22 22 participants, 12 participants completed the DANTALE II test wearing their cochlear implant
23 only; eight participants completed the test wearing both their cochlear implant and their hearing aid.

1 The remaining two participant wore their cochlear implants during testing, but due to
2 miscommunication, no records were made of the use of hearing aids by these participants.
3 Consequently, it is unclear whether or not these two participants also used a hearing aid during
4 testing. While this discrepancy in devices worn during testing is suboptimal, we believe that
5 including all 22 participants in the analyses would yield the most informative results.

6 Digit Span

7 The mean Digit Span Forward for the cochlear implant group ($n = 25$) was $M = 5.27$ digits, 95% CI
8 [4.80 5.80]. The mean Digit Span Forward for the normative sample ($n = 333$; Wechsler, 2007, p.
9 169) was $M = 6.43$ digits, [6.28 6.58]. The mean between-group difference on the Digit Span
10 Forward test was $M = 1.16$ digits, [0.62 1.71]. These results are shown in Fig. 1.

11
12 **Fig 1. Comparison of mean Digit Span Forward scores.** Error bars show 95% confidence
13 intervals. See [40, pp18–19] for an explanation of this type of plot.

14
15 The mean Digit Span Backward for the cochlear implant group ($n = 25$) was $M = 4.07$ digits, [3.53
16 4.53]. The mean Digit Span Backward for the normative sample ($n = 333$) was $M = 4.70$ digits,
17 [4.55 4.85]. The mean between-group difference on the Digit Span Backward test was $M = 0.63$
18 digits, [0.06 1.21]. These results are shown in Fig. 2.

19
20 **Fig 2. Comparison of mean Digit Span Backward scores.** Error bars show 95% confidence
21 intervals.

22

1 **Visual monitoring (PyVDT)**

2 The mean PyVDT A' score (faster presentation rate) was $M = 0.90$, $[0.88\ 0.93]$, $n = 22$.

3 **DANTALE II**

4 The mean DANTALE II SRT was $M = -2.00$ dB, $[-3.20\ -0.80]$, $n = 22$.

5 **Predictors of speech reception**

6 Duration of profound hearing loss and age at profound hearing loss emerged as the best predictors
7 of speech reception, according to our estimates. These predictors accounted for 40 and 19 percent of
8 the variance in speech reception scores, respectively. These results are shown in Figs. 3 and 4. Our
9 analyses did not show the remaining variables to be useful predictors of speech reception. See Table
10 2 for detailed results.

11

12 **Fig 3. DANTALE II speech reception threshold as a function of years of profound hearing**
13 **loss.**

14

15 **Fig 4. DANTALE II speech reception threshold as a function of age at profound hearing loss.**

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Table 2: Predictors of speech reception in noise as measured by the DANTALE II

	<i>n</i>	<i>r</i> ²	<i>b</i>	<i>SE b</i>	95% CI	
					<i>LL</i>	<i>UL</i>
PyVDT (A')	20	0.02				
Intercept			2.21	14.10	-17.00	32.20
Slope			-5.58	15.51	-38.36	15.51
Digit Span Forward	22	0.04				
Intercept			-0.10	3.04	-4.73	7.34
Slope			-0.43	0.55	-1.72	0.44
Digit Span Backward	22	0.02				
Intercept			-4.08	2.48	-9.67	-0.09
Slope			0.46	0.58	-0.62	1.61
CI experience (days)	22	0.09				
Intercept			-3.12	1.52	-6.15	-0.28
Slope			0.00	0.00	0.00	0.00
Profound hearing loss (years)	21	0.40				
Intercept			-4.51	1.81	-7.45	-0.40
Slope			0.10	0.04	0.01	0.16
Age at testing	22	0.00				
Intercept			-3.06	4.62	-13.42	3.35
Slope			0.01	0.08	-0.08	0.20
Age at implantation	22	0.00				
Intercept			-1.51	3.99	-10.50	6.29
Slope			-0.01	0.07	-0.14	0.16
Age at hearing loss	21	0.19				
Intercept			-0.45	1.37	-3.63	1.82
Slope			-0.08	0.04	-0.14	0.01

Note: The analyses are based on the Theil-Sen estimator. Sample sizes differ between analyses because of missing data. See main text for details.

1 **Discussion**

2 Our estimates showed slightly lower mean digit spans in our sample of cochlear implant users
3 compared to the normative sample. The mean between-group difference for Digit Span Forward
4 was around one digit; the mean between-group difference for Digit Span Backward was around half
5 a digit.

6 We were unable to replicate the previously reported association between visual monitoring
7 scores and speech reception. Our study lacks statistical precision (as evidenced by wide confidence
8 intervals) and is inconclusive in this regard. Instead, out of the various predictors included in this
9 study, we found duration of profound hearing loss and age at profound hearing loss to be the most
10 accurate predictors of speech reception in noise. Our results suggest that it becomes increasingly
11 difficult to comprehend speech in noise with each year of profound hearing loss; according to our
12 model estimates, for each year of profound hearing loss, background noise must be attenuated by
13 0.10 dB for speech to be intelligible (see Table 2).

14 **Digit Span**

15 We did not find an association between Digit Span scores and speech reception. This is in contrast
16 to previous studies which reported such a relationship in older adults (e.g., [51]) and in cochlear
17 implanted children [13–15].

18 What is the "real-world" significance of working memory abilities and deficits? Some
19 researchers believe working memory is crucial in everyday life. Baddeley [52, p829], for instance,
20 believes that working memory "supports human thought processes by providing an interface
21 between perception, long-term memory, and action." Weiss, Saklofske, Coalson, and Raiford [53,
22 p71] state that working memory deficits "may create difficulties at work and in daily life
23 functioning". Others, however, believe working memory is of less importance, as long as one meets

1 a certain minimum. Wechsler [54, p83] found that rote memory, such as memory for digits, "seems
2 to be one of those abilities of which a certain absolute minimum is required, but excesses of which
3 seemingly contribute relatively little to the capacities of the individual as a whole." Wechsler [54,
4 p85] goes on to state that "[above] a span of 5 or 6 digits, the value of further improvement in the
5 capacity diminishes very rapidly. A good rote memory is of practical value but correlates very little
6 with higher levels of intelligence."

7 It is important to note that while the Digit Span is included in the WAIS-III, an intelligence
8 test, the present Digit Span results do not reflect the intelligence of our participants or of cochlear
9 implant users in general.

10 Lastly, Lacritz and Cullum [55, p510] claim that "individuals with significant memory
11 deficits may show a larger than expected discrepancy on Digit Span between digits forward and
12 backwards." We found no unusually large discrepancy between the Digit Span Forward and
13 Backward scores of our participants.

14 **Prediction of speech reception**

15 Our finding that duration of hearing loss predicts speech reception scores is in agreement with the
16 literature. In a review of ten studies reporting predictors of speech understanding in cochlear
17 implant users, van Dijk et al. [56, p109] noted that "[the] common finding is that the shorter the
18 duration of deafness, the better the speech understanding with the implant." In addition to duration
19 of deafness, however, van Dijk (1999) lists age as implantation as a typically reported predictor of
20 speech reception. We did not replicate this latter finding.

21 Also, we did not replicate the previously reported finding that visual monitoring predicts
22 speech reception [4]. Possible reasons for this discrepancy include: differences between the original
23 VMT software and our reimplementation (PyVDT), differences in the measures of speech reception

1 used, and/or differences in the populations of implant users sampled in the two studies.

2 The claim that the VMT requires “rapid responding” [25, p6] is perhaps exaggerated, as
3 least regarding the slower VMT-2 rate. Our results suggest that this rate of presentation presented no
4 challenge for our participants. In contrast, Knutson et al. [4] found that the slower VMT rate was
5 the single best cognitive measure predicting audiological outcome.

6 **Recommendations for future studies**

7 Our results indicate that years of hearing loss is a better predictor of speech reception than are the
8 VMT or PyVDT. The former measure is easily obtained, while the latter measures are time-
9 consuming and requires a laptop computer. In its present form, PyVDT did not prove useful, but this
10 may be due to a lack of statistical precision. This may change with future revisions of PyVDT. In
11 any case, future studies using PyVDT should optimize the presentation rates to prevent participants
12 from scoring at ceiling.

13 Future studies investigating the relationship between working memory and speech reception
14 should use more accurate measures. For example, because of limitations inherent in traditional Digit
15 Span testing (e.g., inconsistencies in reading digits aloud to participants), future studies could
16 instead use a computerized adaptive method for digit span testing. One such method is reported by
17 Woods et al. [57] who found that their alternative digit span measure showed enhanced sensitivity
18 and reduced variance compared to the Digit Span.

19 **Limitations**

20 Our participants were aged between 32 and 66. Thus, our study confounds age and years of hearing
21 loss: older participants have been alive longer, and – as a result of their longer lives – have the
22 potential to have been profoundly hearing impaired longer than younger participants. Our analyses

1 did not show a relationship between age and years of profound hearing loss, however. Nor did we
2 find a relationship between age and speech reception. Still, we cannot rule out that such
3 relationships may exist.

4 Measures of residual hearing were not available to us in the present study. Many of our
5 participants had residual hearing on the contralateral ear which is likely to be beneficial in difficult
6 listening conditions.

7 Lastly, while previous studies (e.g., [4]) have looked at preoperative factors predicting
8 implantation outcomes, the current study employed a correlational design, and all of our
9 measurements were obtained postoperatively. This, of course, limits the conclusions that can be
10 drawn. The present findings should not be used to justify decisions regarding which candidates
11 should be selected for implantation. One reason for this is that the research design used is
12 inappropriate for drawing such conclusions.

13 In our earlier questionnaire study (see Participants section), we contacted 250 cochlear
14 implant users, of which 163 responded. Of these 163 respondents, 25 participated in this study.
15 These 25 participants might differ systematically from other cochlear implant users in certain
16 respects (e.g., general health, physical functioning, etc.). Therefore, the generalizability of the
17 findings is limited accordingly.

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4

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9 Supporting Information

10 **S1 Code for the R programming language. R code containing dataset and commands for**
11 **running the statistical analyses.** The R command `source(file.choose)` can be used to run
12 the code. This will generate a table similar to Table 2 in the article. To install the required WRS
13 package, uncomment the appropriate lines inside the file prior to running the code, or follow the
14 instructions provided with the WRS package at <https://github.com/nicebread/WRS>
15 **S2 Dataset. The dataset used in the present study.** The dataset is provided in .csv format.