Learning Effects in Psychophysical Tests of Spectral and Temporal Resolution.

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Abstract

Objectives: Psychophysical tests of spectral and temporal resolution, such as the spectral-ripple discrimination task and the temporal modulation detection test, are valuable tools for evaluation of cochlear implant performance. Both tests correlate with speech intelligibility and are reported to show no instantaneous learning effect. However, some of our previous trials have suggested there is a learning effect over time. The aim of this study was to investigate the test-retest reliability of the 2 tests when measured over time.

Design: Ten adult cochlear implant recipients, experienced with the HiResolution speech coding strategy, participated in this study. Spectral ripple discrimination and temporal modulation detection ability with the HiResolution strategy were assessed both before and after participation in a previous trial that evaluated 2 research speech coding strategies after 2 weeks of home-usage. Each test was repeated six times on each test day.

Results: No improvement was observed for same-day testing. However, comparison of the mean spectral ripple discrimination scores before and after participation in the take-home trial showed improvement from 3.4 to 4.8 ripples per octave (p<0.001). The mean temporal modulation detection thresholds improved from -15.2 dB to -17.4 dB (p=0.035).

Conclusions: There was a clear learning effect over time in the spectral and temporal resolution tasks, but not during same-day testing. Learning effects may stem from perceptual learning, task learning or a combination of those two factors. These results highlight the importance of a proper research design for evaluation of novel speech coding strategies, where the baseline measurement is

45   repeated at the end of the trial to avoid false positive results as a consequence of

46   learning effects.

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INTRODUCTION

Psychophysical tests of spectral and temporal resolution, such as the spectral-ripple test (Won et al. 2007; Drennan et al. 2010; Won et al. 2010; Anderson et al. 2012; Aronoff & Landsberger 2013; Jones et al. 2013) and the temporal modulation detection test, (Shannon 1992; Won et al. 2011; Fraser & McKay 2012) are valuable tools for the evaluation of cochlear implant (CI) hearing during clinical trials. The extent to which the implementation of novel technologies affects the performance of CI recipients is often too mild to detect with traditional speech or music outcome measures. Psychophysical measures are more sensitive to processor changes as they allow for the evaluation of basic abilities, such as spectral and temporal resolution (Buechner et al. 2008; Brendel et al. 2008; Drennan et al. 2010), which are fundamental aspects of how well people hear. Both tests have been shown to correlate independently with vowel, consonant, and speech recognition in CI recipients (Fu 2002; Henry et al. 2005; Won et al. 2007; Won et al. 2013; Holden et al. 2016; Zhou 2017).

It is generally assumed that the evaluation of basic psychophysical capabilities yields a measure of hearing that does not change over time (Won et al. 2007; Drennan et al. 2010). Previous studies have investigated potential 'task learning effects' of spectral and temporal measurements, that is, improvement in performance caused by practice with the task rather than actual improvement in spectral and/or temporal resolution. No task learning effect was found in an acute setting, when tasks were repeated up to nine times (Won et al. 2007; Drennan et al. 2008; Drennan et al. 2010). To the best of our knowledge, only 1 study examined the test-retest reliability of the spectral-ripple threshold measurement over a longer period of time in experienced CI users (Won et al. 2007). No task

73 learning effect was found when repeating the task on separate test days,

74 although, no time interval between the measurements was reported. Drennan et

75 al. (2015) studied learning in both spectral and temporal modulation tests in

76 newly implanted CI users and, on average, did not find a significant

77 improvement over the first 12 months after activation. However, 20% of the

78 individuals significantly improved on both tasks and another 20% significantly

79 deteriorated.

80   The previously mentioned studies suggest that spectral and temporal

81 testing serve as useful, and most probably also reliable diagnostic tools for

82 assessment of CI outcome in a research setting. However, we have observed

83 somewhat different outcomes in our research center. The modified spectral ripple

84 test (SMRT), developed by Aronoff & Landsberger (2013), and the modulation

85 detection threshold (MDT) test, adapted from Bacon & Viemeister (1985), are

86 frequently used in the evaluation of novel processing strategies in the Leiden

87 University Medical Center (LUMC), the Netherlands. As a limited number of CI

88 users are available for research purposes, many of our subjects have participated

89 in multiple studies over the last few years. As a result, these subjects have had

90 substantial practice on the SMRT and MDT test with several different speech

91 coding strategies. We noticed higher SMRT and MDT scores in these more

92 practiced CI users and therefore hypothesize that the psychophysical

93 performance among these CI recipients improved because of this practice.

94   It is well known that CI recipients improve performance in the first few

95 months after implantation (Staller et al. 1997; Rouger et al. 2007; Ruffin et al.

96 2007). It is plausible that this improvement is caused by 'perceptual learning',

97 which is a process by which the ability of the auditory system to process stimuli

5

98 is improved through experience. Also Moberly et al. (2015) suggested that CI

99 users could learn from new speech cues, which might be present in novel speech

100 coding strategies. Repeated testing with the SMRT and MDT test in a research

101 setting with multiple novel speech coding strategies could, therefore, lead to both

102 task and perceptual learning and consequently to improved SMRT and MDT

103 performance. The present study assessed performance on the SMRT and MDT

104 test before and after participation in a previous take-home trial, in which 2

105 experimental speech coding strategies were evaluated.

106 **MATERIALS AND METHODS**

107 **Subjects**

108 A group of 10 adult cochlear implant (CI) recipients who had been implanted

109 with a HiRes90K device with HiFocus 1J or a CII device with HiFocus with a

110 positioner electrode array (Advanced Bionics, Sylmar, CA) at the LUMC were

111 recruited for this study. All had used the Harmony processor programmed with

112 the HiResolution (HiRes) speech coding strategy for multiple years. Subject

113 demographics are shown in Table 1. Ages ranged from 43 to 74 years with a

114 mean of 60.2 years. The average duration of deafness was 26.6 years (range 4-67

115 years) and average implant experience was 98 months (range 31-174 months).

116 Mean phoneme scores on open set Dutch monosyllabic consonant-vowel-

117 consonant (CVC) words in quiet conditions at 65 dB were 89.3% (range 76-96%).

118 **Protocol and speech coding strategies**

119 Spectral ripple discrimination and temporal modulation transfer functions were

120 assessed at baseline (week 0) and 2, 4, and 6 weeks after the baseline measures.

121 Participants were tested twice (at t=0 weeks and t=6 weeks) with their standard

6

122 clinical speech coding strategy, HiRes. This is a bandpass filter based strategy

123 that uses a traditional processing approach in which channel-specific temporal

124 envelopes are extracted and delivered with interleaved, high-rate pulse trains.

125 More detailed information about this speech coding strategy is provided by Firszt

126 (2003).

127 The examinations at week 2 and 4 were part of a separate take-home trial, in

128 which 2 variations of the HiRes speech coding strategy, which applied different

129 filtering techniques, were evaluated. The 2 experimental strategies, HiRes FFT

130 and HiRes Optima (Advanced Bionics, reference note 1), utilize a finite impulse

131 response filter in conjunction with Fast Fourier Transformation (FFT)

132 processing. HiRes Optima also uses current steering to create up to 135 virtual

133 spectral channels. In fact, it is a more energy-efficient variation of HiRes Fidelity

134 120 (Firszt et al. 2009). As the number of excitable channels is increased with

135 HiRes Optima, an improved performance on the SMRT is expected as compared

136 to both HiRes and HiRes FFT, as was demonstrated for HiRes Fidelity 120 by

137 Drennan et al. (2010). However, these authors also argued that FFT processing

138 potentially decreases temporal resolution, due to spectral smearing. Therefore,

139 both HiRes FFT and HiRes Optima might decrease performance on the MDT

140 test. To eliminate order and practice effects, the participants received the 2

141 experimental take-home strategies in randomized order and had the chance to

142 adapt to the strategies during the 2 weeks prior to the testing. In this paper, the

143 randomization allows for the evaluation of test date effects (between week 2 and

144 4) while minimizing the effects of processing strategy. In other words, in the

145 paired comparison between performance at week 2 and 4, half of the participants

146 was using HiRes FFT and half was using HiRes Optima at each test session.

147 Because the order of strategy was randomized, the effect of strategy was

148 minimal. The current study was approved by the Medical Ethical Committee of

149 the LUMC (ref. P02.106.Y).

150 **Psychophysical testing:**

151 During all psychophysical tasks, the listeners were seated in a double-walled

152 sound-attenuating booth. Sounds were presented via a single loudspeaker, placed

153 1 meter from the listener at 0 degrees and level with the listener's head. Subjects

154 received instructions for the psychophysical tests and then practiced the tasks six

155 times or more if necessary, to avoid learning in the actual test setting. Listeners

156 responded using a mouse with a custom computer interface, or they responded

157 verbally when they were unable to use the mouse (for example subject 10 was

158 visually impaired). All stimuli were presented at 65 dB (SPL).

159 Spectral resolution was examined with the spectral-temporally modulated

160 ripple test (SMRT) as developed by Aronoff & Landsberger (2013). In this

161 adaptive 3-alternative forced choice task, listeners were asked to discriminate a

162 spectrally rippled stimulus, that is, a stimulus that is amplitude modulated in

163 the frequency domain, from a reference stimulus. The reference stimuli had fixed

164 ripple densities of 20 ripples per octave (RPO), whereas the ripple density of the

165 target stimulus was modified until the listener was unable to discriminate

166 between the stimuli. The SMRT differs from previous spectral ripple tests (e.g.

167 Henry & Turner 2003) in that the ripple stimuli are modified. The SMRT uses a

168 spectral ripple with a modulation phase that drifts with time (See fig. 1a in

169 Aronoff & Landsberger 2013), thereby avoiding loudness cues and edge effects.

170 No feedback about the correct answer was given. The procedure was repeated six

171 times per testing run, and the estimated thresholds were averaged as the final

172 SMRT score.

173   The temporal modulation transfer function (TMTF) test, a 2-alternative

174 forced choice measure of temporal resolution, was used to determine the

175 modulation depth detection threshold (MDT) (Won et al. 2011). Two 1-second

176 intervals consisting of wide band noise were presented to the listener. While the

177 reference stimulus was unmodulated, the target stimulus was amplitude

178 modulated in the time domain with a frequency of 100 Hz and a starting

179 modulation depth of 100%, because these conditions, when combined with

180 spectral ripple thresholds, accounted for the highest amount of speech variance

181 in previous studies (Won et al. 2011). Subjects were instructed to choose the

182 interval that contained the modulated noise after which feedback of the correct

183 answer was provided. A 2-down, 1-up adaptive procedure was used to obtain

184 MDTs in dB relative to 100% modulation [20log10(modulation depth)]. The

185 average of six tracking histories provided the final MDT score.

186 **Statistical analysis**

187 A 2-way repeated measures analysis of variance (ANOVA) using within-subject

188 factors of 'visit' (Week numbers) and 'repetition number' (Repetition number 1-6)

189 were used to determine if there was a main effect of visit, repetition number, and

190 an interaction between those two factors. Because two different strategies were

191 examined in randomized order in week 2 and 4, those weeks could not be

192 compared to week 0 or 6. Therefore, only week 0 and 6 were compared to each

193 other and week 2 was compared to week 4. SPSS Statistics Version 20 was used

194 for calculations.

RESULTS

196 Individual and mean SMRT scores per test day are demonstrated in Figures 1A

197 and 1B. The average scores of the six repetitions was 3.4 RPO at baseline and 4.2

198 RPO, 5.0 RPO, and 4.8 RPO at weeks 2, 4, and 6, respectively. The results from a

199 2-way repeated-measures ANOVA indicated a highly significant improvement

200 between baseline and 6-week SMRT thresholds ($F_{1,9}=52.2$, $p<0.001$), which was

201 present for all ten subjects (Fig.1). No significant effect of repetition number

202 ($F_{5,45}=1.5$, $p=0.195$) or interaction between visit and repetition number

203 ($F_{5,45}=1.398$, $p=0.243$) was observed. There was no significant difference

204 between SMRT scores at week 2 and 4 ($F_{1,9}=1.755$, $p=0.218$) (Fig. 1B). Figure 2

205 shows the individual and mean SMRT thresholds as a function of trial number at

206 instantaneous testing, i.e. repeating the task on the same test day. A 2-way

207 repeated-measures ANOVA using the Greenhouse-Geisser correction revealed no

208 learning over the course of the six repeated runs on a given test day when all 4

209 test days were included ($F_{2.4,21.5}=2.347$, $p=0.112$). When comparing the first

210 with the last measurements in the sequence of six, a borderline significant

211 improvement of 0.7 RPO was found ($F_{1,9}=5.012$, $p=0.052$).

212 Individual and mean MDT scores are shown in Figures 3A and 3B. The mean

213 MDT scores at weeks 0, 2, 4, and 6 were -15.2 dB, -16.5 dB, -17.2 dB, and -17.4

214 dB, respectively, relative to 100% amplitude modulation. A 2-way repeated-

215 measures ANOVA showed that there was a significant improvement between the

216 first and second six repetitions with the HiRes speech coding strategy, i.e. week 0

217 versus week 6 ($F_{1,9}=6.108$, $p=0.035$) (Fig. 3A). No effect of repetition number

218 ($F_{5,45}=0.965$, $p=0.449$) or interaction between visit and repetition number

219 (F5,45=0.483, p=0.787) was observed. As 1 outlier was observed in this analysis

220 (subject 1), the repeated-measures ANOVA was repeated while excluding the

221 outlier, resulting in mean scores of -16.1 dB at baseline and -17.4 at 6 weeks. The

222 improvement appeared to still be highly statistically significant (F1,8=23.7,

223 p=0.001), and still revealed no effect of repetition number (F5,40=1.018, p=0.420)

224 or interaction between visit and repetition number (F5,40=0.709, p=0.620). The

225 MDT scores at weeks 2 and 4 were not significantly different from each other

226 (F1,9=0.608, p=0.456) (Fig. 3B) and a 2-way repeated-measures ANOVA using

227 the Greenhouse-Geisser correction to adjust for non-sphericity revealed no effect

228 of repetition number when all 4 test days were included (F2.2, 19.9=0.967,

229 p=0.405). Moreover, no improvement was observed between the first and last of

230 the six repetitions (F1,9=2.289, p=0.165). Altogether, these findings indicated no

231 instantaneous learning effect (Fig. 4). A Pearson product-moment correlation

232 coefficient was computed to assess the relationship between the SMRT and MDT

233 scores, and revealed a significant correlation between the two measures,

234 R^2=0.298, p<0.001.

235

236   **DISCUSSION**

237 The present study demonstrated a clear significant learning effect over time for

238 both the SMRT and the MDT test after repeated examination with the use of

239 different speech coding strategies. Group spectral-ripple discrimination ability

240 improved from 3.4 RPO at baseline to 4.8 RPO at the retest measurement after

241 participation in a clinical trial. The difference was significant on the individual

242 level in five out of ten subjects. The MDT results improved from -15.2 dB to -17.4

243   dB, a difference of -2.2 dB group-wide in the same time interval. Two out of ten

244   individual participants improved significantly. None of the listeners deteriorated

245   in performance and, in line with previous literature (Won et al. 2007; Drennan et

246   al. 2008; Drennan et al. 2010), no learning was observed for either task in an

247   acute setting.

248   Although no instantaneous learning effect was detected in this or previous

249   studies, there are also studies that conclude that there is no learning over time.

250   However, this previous research on learning effects mainly focused on acute

251   settings, and if long-term learning was assessed, either the duration was poorly

252   reported or learning effects after longer time intervals (at least 2 months) were

253   investigated (Won et al. 2007; Drennan et al. 2014; Drennan et al. 2015). During

254   clinical take-home trials, when the presence of a potential learning effect is

255   essential for the interpretation of results, participants are typically exposed to

256   multiple speech coding strategies and execute the psychophysical tasks relatively

257   frequently, e.g., every 2-4 weeks. This makes it essential to identify learning

258   effects in these time frames.

259   Multiple practice sessions with rather short time intervals introduce 2

260   potential risks; perceptual and task learning. Exposure to new speech-coding

261   strategies, and therefore novel speech cues, leads to perceptual learning. Because

262   the study population in this study participated in a clinical trial between baseline

263   and retest measurements, they did get a chance to adapt to different speech cues

264   and learn new auditory percepts. This perceptual learning could have potentially

265   been used in the spectral and/or temporal discrimination tasks (Moberly et al.

266   2015). On the other hand, speech scores were also assessed during this trial, for

267 which no improvement was observed ($F_{1,9}=0.826$, $p=0.387$). The lack of a

268 correlation between improvement of the speech scores and the SMRT or MDT

269 scores ($R=0.039$ and $R=0.073$ respectively), suggests that the potential effect of

270 perceptual learning is limited. It is reasonable to assume that repeated

271 psychophysical testing in a short period of time could cause task learning.

272 Moreover, it is well-known that perceptual learning amplifies this task learning

273 because of a so-called "carryover effect" (Liu 1999; Liu & Weinshall 2000;

274 Donaldson et al. 2011). A carryover effect is an effect, or ability, that carries over

275 from one experimental condition to another. When time intervals between test

276 sessions are sufficient, like in the study of Drennan et al. (2015), a carryover

277 effect can be considered as (at least partially) extinguished. In other words, a so-

278 called "wash-out period" of sufficient duration compensates for the carryover

279 effect. Moreover, as the purpose of Drennan et al. (2015) was to examine whether

280 basic spectral and temporal discrimination abilities would change over the first

281 year of implant use, they did not vary speech coding strategies. Hence, no

282 perceptual learning induced by the use of novel speech coding strategies could

283 occur. Given the frequency of test intervals in the current study, which was

284 comparable to many other take-home studies (e.g. Holden et al. 2013; Neben et

285 al. 2013; Frijns et al. 2013), it is possible that the duration between visits was

286 shorter than the wash-out period and therefore a carryover effect cannot be ruled

287 out. Although it is clear that a learning effect was present for both tests, the

288 current study cannot identify the exact mechanism for this effect. It could be due

289 to task learning, perceptual learning by participating in a clinical trial, or a

290 combination of both factors.

291   Our results could also partially be explained by the upward trend in

292   motivation of participants, and the placebo effect of any new speech coding

293   strategy. Moreover, the contrasting results found in this study compared with

294   previous work, could, although unlikely, be attributed to the use of different

295   versions of the psychoacoustic measures. For example, Drennan et al. (2014) used

296   a non-adaptive clinical version of the spectral ripple test, which differed

297   considerably from the spectral ripple task that was used in the current study. For

298   example, the current spectral ripple task implemented a temporal effect to avoid

299   potential loudness cues. This resulted in a significant, though fairly low,

300   correlation between SMRT and MDT scores, implying that the SMRT does not

301   purely measure spectral resolution, but is also influenced by temporal effects.

302   This emphasizes the need for an improved measure of spectral resolution, that is

303   less influenced by both loudness and temporal cues.

304   Because the order in which the two experimental strategies were examined

305   in this study was randomized, an extra analysis between the second and third

306   test day, irrespective of the speech coding strategy, could be performed. No

307   significant difference was found between the test days for either task, implying

308   that no learning, or too little effect size to reach sufficient power, is present after

309   2 blocks of testing on separate days. Unfortunately, the number of practice

310   sessions that are necessary for the learning effect to be completely extinguished

311   is unclear and information about the effect size of learning in the MDT test and

312   SMRT is not provided. In that light, it would have been helpful if basic HiRes

313   scores were evaluated at each session, regardless of what condition the subjects

314   were sent home with, although the fatigue that comes with multiple test sessions

315   on one day introduces another bias. A placebo controlled trial, in which

316   participants perform the psychophysical tasks multiple times, on separate test

317   days, with the same speech coding strategy (with a "fake" remapping in which

318   the subject may think that the strategy is different, but in fact is not), would

319   provide us with more specific information. Nevertheless, this study provides us

320   with sufficient evidence that a learning effect is present in the two tasks.

321   These results do not diminish the value of psychophysical testing for the

322   evaluation of newly developed speech coding strategies; rather, they emphasize

323   the importance of a proper, randomized research design. As a carryover effect

324   could be the cause of learning, it should be dealt with by allowing sufficient time

325   between test dates to "wash-out" the effect of the previous test. Moreover, it is

326   important to incorporate a second testing phase with the baseline speech coding

327   strategy at the end of the trial, in addition to the initial baseline measurement, if

328   one wants to conclude that one of the coding strategies under test is really

329   improving speech perception. In line with this, Donaldson et al. (2011) found a

330   significant improvement in vowel recognition the second time the baseline

331   strategy was evaluated and used these results for comparison with the research

332   strategy. Another example is the study of Vermeire et al. (2010), where an

333   experimental strategy was examined acutely and after 1, 3, 6 and 12 months of

334   usage. They found a significant improvement in speech intelligibility in noise

335   with the experimental strategy over time. However, switching back to the

336   baseline strategy resulted in a similar improvement (see fig.1. of Vermeire et al.

337   (2010)), underlining the importance of comparing speech perception results with

338   a second baseline measurement. This helps to avoid misinterpretation of

339   improvements due to learning effects as true differences between strategies.

340

CONCLUSIONS

341

342   The SMRT and MDT tasks show a clear learning effect over time when examined

343   relatively frequently in a clinical trial. Although an unmistakable explanation

344   has not been shown, these results emphasize the vigilance with which these

345   psychophysical test should be used in clinical trials, for the explicit reason that

346   they are assumed to not change over time. Moreover, great caution with respect

347   to (specifically long-term) learning effects is advised for the development of new

348   psychophysical measures.

349

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450

FIGURES

Figure 1

A. Individual and mean spectral ripple thresholds for 10 subjects (HiRes)

B. The same as A, now for the HiResFFT and Optima strategies

Figure 2.

Effects of instantaneous learning for the spectral ripple task. The figure shows

individual and mean spectral ripple thresholds as a function of trial number

based on data from 10 subjects at 4 test intervals.

Figure 3

A. Individual and mean modulation detection thresholds for 10 subjects (HiRes)

B. The same as A, now for the HiResFFT and Optima strategies.

Figure 4.

Effects of instantaneous learning for the Temporal Modulation Transfer Function

test. The figure shows individual and mean Modulation detection thresholds as a

function of trial number based on data from 10 subjects at 4 test intervals.