Learning Effects in Psychophysical Tests of Spectral and Temporal Resolution.

Monique A. M. de Jong, MD[1], Jeroen J. Briaire, PhD[1], and prof. Johan H.M. Frijns, MD, PhD[12]

[1] ENT Department, Leiden University Medical Centre, Leiden, The Netherlands

[2] Leiden Institute for Brain and Cognition, Leiden University, Leiden, The Netherlands

Financial Disclosures/Conflicts of Interest: This research was supported by non-restrictive research funding from Advanced Bionics.

Corresponding author: Johan H.M. Frijns, ENT Department, Leiden University Medical Centre

PO Box 9600

2300 RC Leiden, The Netherlands

Email: J.H.M.Frijns@lumc.nl

Telephone number: +31 (0)71 52 611 79

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

repeated at the end of the trial to avoid false positive results as a consequence of learning effects.

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 learning effect was found when repeating the task on separate test days, although, no time interval between the measurements was reported. Drennan et al. (2015) studied learning in both spectral and temporal modulation tests in newly implanted CI users and, on average, did not find a significant improvement over the first 12 months after activation. However, 20% of the individuals significantly improved on both tasks and another 20% significantly deteriorated.

The previously mentioned studies suggest that spectral and temporal testing serve as useful, and most probably also reliable diagnostic tools for assessment of CI outcome in a research setting. However, we have observed somewhat different outcomes in our research center. The modified spectral ripple test (SMRT), developed by Aronoff & Landsberger (2013), and the modulation detection threshold (MDT) test, adapted from Bacon & Viemeister (1985), are frequently used in the evaluation of novel processing strategies in the Leiden University Medical Center (LUMC), the Netherlands. As a limited number of CI users are available for research purposes, many of our subjects have participated in multiple studies over the last few years. As a result, these subjects have had substantial practice on the SMRT and MDT test with several different speech coding strategies. We noticed higher SMRT and MDT scores in these more practiced CI users and therefore hypothesize that the psychophysical performance among these CI recipients improved because of this practice.

It is well known that CI recipients improve performance in the first few months after implantation (Staller et al. 1997; Rouger et al. 2007; Ruffin et al. 2007). It is plausible that this improvement is caused by ‘perceptual learning’, which is a process by which the ability of the auditory system to process stimuli is improved through experience. Also Moberly et al. (2015) suggested that CI users could learn from new speech cues, which might be present in novel speech coding strategies. Repeated testing with the SMRT and MDT test in a research setting with multiple novel speech coding strategies could, therefore, lead to both task and perceptual learning and consequently to improved SMRT and MDT performance. The present study assessed performance on the SMRT and MDT test before and after participation in a previous take-home trial, in which 2 experimental speech coding strategies were evaluated.

MATERIALS AND METHODS

Subjects

A group of 10 adult cochlear implant (CI) recipients who had been implanted with a HiRes90K device with HiFocus 1J or a CII device with HiFocus with a positioner electrode array (Advanced Bionics, Sylmar, CA) at the LUMC were recruited for this study. All had used the Harmony processor programmed with the HiResolution (HiRes) speech coding strategy for multiple years. Subject demographics are shown in Table 1. Ages ranged from 43 to 74 years with a mean of 60.2 years. The average duration of deafness was 26.6 years (range 4-67 years) and average implant experience was 98 months (range 31-174 months). Mean phoneme scores on open set Dutch monosyllabic consonant-vowel-consonant (CVC) words in quiet conditions at 65 dB were 89.3% (range 76-96%).

Protocol and speech coding strategies

Spectral ripple discrimination and temporal modulation transfer functions were assessed at baseline (week 0) and 2, 4, and 6 weeks after the baseline measures. Participants were tested twice (at t=0 weeks and t=6 weeks) with their standard clinical speech coding strategy, HiRes. This is a bandpass filter based strategy that uses a traditional processing approach in which channel-specific temporal envelopes are extracted and delivered with interleaved, high-rate pulse trains. More detailed information about this speech coding strategy is provided by Firszt (2003).

The examinations at week 2 and 4 were part of a separate take-home trial, in which 2 variations of the HiRes speech coding strategy, which applied different filtering techniques, were evaluated. The 2 experimental strategies, HiRes FFT and HiRes Optima (Advanced Bionics, reference note 1), utilize a finite impulse response filter in conjunction with Fast Fourier Transformation (FFT) processing. HiRes Optima also uses current steering to create up to 135 virtual spectral channels. In fact, it is a more energy-efficient variation of HiRes Fidelity 120 (Firszt et al. 2009). As the number of excitable channels is increased with HiRes Optima, an improved performance on the SMRT is expected as compared to both HiRes and HiRes FFT, as was demonstrated for HiRes Fidelity 120 by Drennan et al. (2010). However, these authors also argued that FFT processing potentially decreases temporal resolution, due to spectral smearing. Therefore, both HiRes FFT and HiRes Optima might decrease performance on the MDT test. To eliminate order and practice effects, the participants received the 2 experimental take-home strategies in randomized order and had the chance to adapt to the strategies during the 2 weeks prior to the testing. In this paper, the randomization allows for the evaluation of test date effects (between week 2 and 4) while minimizing the effects of processing strategy. In other words, in the paired comparison between performance at week 2 and 4, half of the participants was using HiRes FFT and half was using HiRes Optima at each test session.

Because the order of strategy was randomized, the effect of strategy was minimal. The current study was approved by the Medical Ethical Committee of the LUMC (ref. P02.106.Y).

Psychophysical testing:

During all psychophysical tasks, the listeners were seated in a double-walled sound-attenuating booth. Sounds were presented via a single loudspeaker, placed 1 meter from the listener at 0 degrees and level with the listener's head. Subjects received instructions for the psychophysical tests and then practiced the tasks six times or more if necessary, to avoid learning in the actual test setting. Listeners responded using a mouse with a custom computer interface, or they responded verbally when they were unable to use the mouse (for example subject 10 was visually impaired). All stimuli were presented at 65 dB (SPL).

Spectral resolution was examined with the spectral-temporally modulated ripple test (SMRT) as developed by Aronoff & Landsberger (2013). In this adaptive 3-alternative forced choice task, listeners were asked to discriminate a spectrally rippled stimulus, that is, a stimulus that is amplitude modulated in the frequency domain, from a reference stimulus. The reference stimuli had fixed ripple densities of 20 ripples per octave (RPO), whereas the ripple density of the target stimulus was modified until the listener was unable to discriminate between the stimuli. The SMRT differs from previous spectral ripple tests (e.g. Henry & Turner 2003) in that the ripple stimuli are modified. The SMRT uses a spectral ripple with a modulation phase that drifts with time (See fig. 1a in Aronoff & Landsberger 2013), thereby avoiding loudness cues and edge effects. No feedback about the correct answer was given. The procedure was repeated six times per testing run, and the estimated thresholds were averaged as the final SMRT score.

The temporal modulation transfer function (TMTF) test, a 2-alternative forced choice measure of temporal resolution, was used to determine the modulation depth detection threshold (MDT) (Won et al. 2011). Two 1-second intervals consisting of wide band noise were presented to the listener. While the reference stimulus was unmodulated, the target stimulus was amplitude modulated in the time domain with a frequency of 100 Hz and a starting modulation depth of 100%, because these conditions, when combined with spectral ripple thresholds, accounted for the highest amount of speech variance in previous studies (Won et al. 2011). Subjects were instructed to choose the interval that contained the modulated noise after which feedback of the correct answer was provided. A 2-down, 1-up adaptive procedure was used to obtain MDTs in dB relative to 100% modulation [20log10(modulation depth)]. The average of six tracking histories provided the final MDT score.

Statistical analysis

A 2-way repeated measures analysis of variance (ANOVA) using within-subject factors of 'visit' (Week numbers) and 'repetition number' (Repetition number 1-6) were used to determine if there was a main effect of visit, repetition number, and an interaction between those two factors. Because two different strategies were examined in randomized order in week 2 and 4, those weeks could not be compared to week 0 or 6. Therefore, only week 0 and 6 were compared to each other and week 2 was compared to week 4. SPSS Statistics Version 20 was used for calculations.

RESULTS

Individual and mean SMRT scores per test day are demonstrated in Figures 1A and 1B. The average scores of the six repetitions was 3.4 RPO at baseline and 4.2 RPO, 5.0 RPO, and 4.8 RPO at weeks 2, 4, and 6, respectively. The results from a 2-way repeated-measures ANOVA indicated a highly significant improvement between baseline and 6-week SMRT thresholds ($F_{1,9}=52.2$, $p<0.001$), which was present for all ten subjects (Fig.1). No significant effect of repetition number ($F_{5,45}=1.5$, $p=0.195$) or interaction between visit and repetition number ($F_{5,45}=1.398$, $p=0.243$) was observed. There was no significant difference between SMRT scores at week 2 and 4 ($F_{1,9}=1.755$, $p=0.218$) (Fig. 1B). Figure 2 shows the individual and mean SMRT thresholds as a function of trial number at instantaneous testing, i.e. repeating the task on the same test day. A 2-way repeated-measures ANOVA using the Greenhouse-Geisser correction revealed no learning over the course of the six repeated runs on a given test day when all 4 test days were included ($F_{2.4,21.5}=2.347$, $p=0.112$). When comparing the first with the last measurements in the sequence of six, a borderline significant improvement of 0.7 RPO was found ($F_{1,9}=5.012$, $p=0.052$).

Individual and mean MDT scores are shown in Figures 3A and 3B. The mean MDT scores at weeks 0, 2, 4, and 6 were -15.2 dB, -16.5 dB, -17.2 dB, and -17.4 dB, respectively, relative to 100% amplitude modulation. A 2-way repeated-measures ANOVA showed that there was a significant improvement between the first and second six repetitions with the HiRes speech coding strategy, i.e. week 0 versus week 6 ($F_{1,9}=6.108$, $p=0.035$) (Fig. 3A). No effect of repetition number ($F_{5,45}=0.965$, $p=0.449$) or interaction between visit and repetition number

(F5,45=0.483, p=0.787) was observed. As 1 outlier was observed in this analysis (subject 1), the repeated-measures ANOVA was repeated while excluding the outlier, resulting in mean scores of -16.1 dB at baseline and -17.4 at 6 weeks. The improvement appeared to still be highly statistically significant (F1,8=23.7, p=0.001), and still revealed no effect of repetition number (F5,40=1.018, p=0.420) or interaction between visit and repetition number (F5,40=0.709, p=0.620). The MDT scores at weeks 2 and 4 were not significantly different from each other (F1,9=0.608, p=0.456) (Fig. 3B) and a 2-way repeated-measures ANOVA using the Greenhouse-Geisser correction to adjust for non-sphericity revealed no effect of repetition number when all 4 test days were included (F2.2, 19.9=0.967, p=0.405). Moreover, no improvement was observed between the first and last of the six repetitions (F1,9=2.289, p=0.165). Altogether, these findings indicated no instantaneous learning effect (Fig. 4). A Pearson product-moment correlation coefficient was computed to assess the relationship between the SMRT and MDT scores, and revealed a significant correlation between the two measures, $R^2=0.298$, $p<0.001$.

DISCUSSION

The present study demonstrated a clear significant learning effect over time for both the SMRT and the MDT test after repeated examination with the use of different speech coding strategies. Group spectral-ripple discrimination ability improved from 3.4 RPO at baseline to 4.8 RPO at the retest measurement after participation in a clinical trial. The difference was significant on the individual level in five out of ten subjects. The MDT results improved from -15.2 dB to -17.4

dB, a difference of -2.2 dB group-wide in the same time interval. Two out of ten individual participants improved significantly. None of the listeners deteriorated in performance and, in line with previous literature (Won et al. 2007; Drennan et al. 2008; Drennan et al. 2010), no learning was observed for either task in an acute setting.

Although no instantaneous learning effect was detected in this or previous studies, there are also studies that conclude that there is no learning over time. However, this previous research on learning effects mainly focused on acute settings, and if long-term learning was assessed, either the duration was poorly reported or learning effects after longer time intervals (at least 2 months) were investigated (Won et al. 2007; Drennan et al. 2014; Drennan et al. 2015). During clinical take-home trials, when the presence of a potential learning effect is essential for the interpretation of results, participants are typically exposed to multiple speech coding strategies and execute the psychophysical tasks relatively frequently, e.g., every 2-4 weeks. This makes it essential to identify learning effects in these time frames.

Multiple practice sessions with rather short time intervals introduce 2 potential risks; perceptual and task learning. Exposure to new speech-coding strategies, and therefore novel speech cues, leads to perceptual learning. Because the study population in this study participated in a clinical trial between baseline and retest measurements, they did get a chance to adapt to different speech cues and learn new auditory percepts. This perceptual learning could have potentially been used in the spectral and/or temporal discrimination tasks (Moberly et al. 2015). On the other hand, speech scores were also assessed during this trial, for which no improvement was observed (F1,9=0.826, p=0.387). The lack of a correlation between improvement of the speech scores and the SMRT or MDT scores (R=0.039 and R=0.073 respectively), suggests that the potential effect of perceptual learning is limited. It is reasonable to assume that repeated psychophysical testing in a short period of time could cause task learning. Moreover, it is well-known that perceptual learning amplifies this task learning because of a so-called “carryover effect” (Liu 1999; Liu & Weinshall 2000; Donaldson et al. 2011). A carryover effect is an effect, or ability, that carries over from one experimental condition to another. When time intervals between test sessions are sufficient, like in the study of Drennan et al. (2015), a carryover effect can be considered as (at least partially) extinguished. In other words, a so-called “wash-out period” of sufficient duration compensates for the carryover effect. Moreover, as the purpose of Drennan et al. (2015) was to examine whether basic spectral and temporal discrimination abilities would change over the first year of implant use, they did not vary speech coding strategies. Hence, no perceptual learning induced by the use of novel speech coding strategies could occur. Given the frequency of test intervals in the current study, which was comparable to many other take-home studies (e.g. Holden et al. 2013; Neben et al. 2013; Frijns et al. 2013), it is possible that the duration between visits was shorter than the wash-out period and therefore a carryover effect cannot be ruled out. Although it is clear that a learning effect was present for both tests, the current study cannot identify the exact mechanism for this effect. It could be due to task learning, perceptual learning by participating in a clinical trial, or a combination of both factors.

Our results could also partially be explained by the upward trend in motivation of participants, and the placebo effect of any new speech coding strategy. Moreover, the contrasting results found in this study compared with previous work, could, although unlikely, be attributed to the use of different versions of the psychoacoustic measures. For example, Drennan et al. (2014) used a non-adaptive clinical version of the spectral ripple test, which differed considerably from the spectral ripple task that was used in the current study. For example, the current spectral ripple task implemented a temporal effect to avoid potential loudness cues. This resulted in a significant, though fairly low, correlation between SMRT and MDT scores, implying that the SMRT does not purely measure spectral resolution, but is also influenced by temporal effects. This emphasizes the need for an improved measure of spectral resolution, that is less influenced by both loudness and temporal cues.

Because the order in which the two experimental strategies were examined in this study was randomized, an extra analysis between the second and third test day, irrespective of the speech coding strategy, could be performed. No significant difference was found between the test days for either task, implying that no learning, or too little effect size to reach sufficient power, is present after 2 blocks of testing on separate days. Unfortunately, the number of practice sessions that are necessary for the learning effect to be completely extinguished is unclear and information about the effect size of learning in the MDT test and SMRT is not provided. In that light, it would have been helpful if basic HiRes scores were evaluated at each session, regardless of what condition the subjects were sent home with, although the fatigue that comes with multiple test sessions on one day introduces another bias. A placebo controlled trial, in which participants perform the psychophysical tasks multiple times, on separate test days, with the same speech coding strategy (with a “fake” remapping in which the subject may think that the strategy is different, but in fact is not), would provide us with more specific information. Nevertheless, this study provides us with sufficient evidence that a learning effect is present in the two tasks.

These results do not diminish the value of psychophysical testing for the evaluation of newly developed speech coding strategies; rather, they emphasize the importance of a proper, randomized research design. As a carryover effect could be the cause of learning, it should be dealt with by allowing sufficient time between test dates to “wash-out” the effect of the previous test. Moreover, it is important to incorporate a second testing phase with the baseline speech coding strategy at the end of the trial, in addition to the initial baseline measurement, if one wants to conclude that one of the coding strategies under test is really improving speech perception. In line with this, Donaldson et al. (2011) found a significant improvement in vowel recognition the second time the baseline strategy was evaluated and used these results for comparison with the research strategy. Another example is the study of Vermeire et al. (2010), where an experimental strategy was examined acutely and after 1, 3, 6 and 12 months of usage. They found a significant improvement in speech intelligibility in noise with the experimental strategy over time. However, switching back to the baseline strategy resulted in a similar improvement (see fig.1. of Vermeire et al. (2010)), underlining the importance of comparing speech perception results with a second baseline measurement. This helps to avoid misinterpretation of improvements due to learning effects as true differences between strategies.

CONCLUSIONS

The SMRT and MDT tasks show a clear learning effect over time when examined relatively frequently in a clinical trial. Although an unmistakable explanation has not been shown, these results emphasize the vigilance with which these psychophysical test should be used in clinical trials, for the explicit reason that they are assumed to not change over time. Moreover, great caution with respect to (specifically long-term) learning effects is advised for the development of new psychophysical measures.

Acknowledgements

We thank all our participants for their time and effort during this trial. The work was financially supported by Advanced Bionics.

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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.