Citation/Reference	Denys S, Hofmann M, van Wieringen A, Wouters J Improving the efficiency of the Digit Triplet Test using digit scoring with variable adaptive step sizes Int. J. Audiol, 1-8, Jun 2019
Archived version	Author manuscript: the content is identical to the content of the published paper, but without the final typesetting by the publisher
Published version	https://www.tandfonline.com/doi/abs/10.1080/14992027.2019.1622042?journalCode=ijja20
DOI	10.1080/14992027.2019.1622042
Journal homepage	https://www.tandfonline.com/action/journalInformation?show=aimsScope&journalCode=IJJA20
Author contact	sam.denys@kuleuven.be , jan.wouters@med.kuleuven.be

2 **Improving the efficiency of the Digit Triplet Test using digit scoring with**
3 **variable adaptive step sizes**

4 Sam Denys*-Michael Hofmann, Astrid van Wieringen and Jan Wouters

5 *KU Leuven, Department of Neurosciences, ExpORL, Leuven, Belgium*

6 *Herestraat 49 - box 721, 3000 Leuven, Belgium, sam.denys@kuleuven.be

Acknowledgements: The authors thank Erica Schoonjans, Babette Van De Velde and Lien Zwysen (master students of the Speech-Language Pathology and Audiology program, KU Leuven) for their help with participant recruitment and data collection. Heleen Luts is acknowledged for her methodological support.

Portions of this article were presented at the European Federation of Audiology (EFAS) conference (Istanbul, Turkey, May 27-30, 2015).

This work was supported by a TBM-FWO grant from the Research Foundation Flanders (grant number T002216N) and by KU Leuven project OT/12/98.

The authors report no conflicts of interest.

Improving the efficiency of the Digit Triplet Test using digit scoring with variable adaptive step sizes

Objective: To investigate modifications of the Flemish Digit Triplet Test (DTT) to improve its efficiency, i.e. the use of a low-pass filtered noise and variable adaptive step sizes according to a digit scoring procedure, targeting different recognition probabilities. Design and study sample: Speech reception thresholds (SRT) were evaluated in terms of their test-retest reliability and correlation with pure tone averages (PTA) in a group of 68 adult participants with different degrees of hearing impairment. Results: The use of a low-pass filtered noise did not result in better test-retest reliability or an improved SRT-PTA correlation. Using digit scoring with adaptive step sizes parametrized to target a recognition probability of 79% (D79), corresponding to the recognition probability of the currently used DTT with triplet scoring and fixed adaptive step sizes of 2 dB, increased test-retest reliability. Lower recognition probabilities of 57 and 35% demonstrated worse reliability and worse SRT-PTA correlations. Conclusions: Given the increased test-retest reliability of D79, a similar reliability as for the currently used DTT could be obtained after considerably fewer trials, leading to a profit in test duration.

Keywords: Digit Triplet Test; efficiency; hearing screening

Main text introduction

Digit Triplet Tests (DTT) are valid, reliable and robust speech-in-noise tests for the detection of hearing impairment. They use a limited set of highly familiar speech items, i.e. three-digit combinations, which are presented in a noise masker to estimate an individual's speech reception threshold (SRT), i.e. the signal-to-noise ratio (SNR) that is required for a certain recognition probability. For this purpose, an adaptive procedure in which the SNR is varied per triplet is used and an averaged SNR over n -presentation levels or trials is calculated.

Today, fifteen years after their original conception (Smits et al, 2004), DTTs are available in multiple languages (Zokoll et al, 2012; Zokoll et al, 2013; Potgieter et al, 2015; Willberg et al, 2016) for large-scale hearing screening over telephone (Smits & Houtgast, 2005; Jansen et al, 2010; Watson et al, 2012), the internet (Smits et al, 2006; Vlaming et al, 2014) or via mobile devices, such as smartphones (Potgieter et al, 2018a; De Sousa et al, 2018) and tablet computers (Denys et al, 2018). Also, their development principles have been consolidated in a consensus paper by the International Collegium of Rehabilitative Audiology (Akeroyd et al, 2015).

DTT-SRTs agree strongly with pure tone averages (PTA) derived from diagnostic pure tone audiometry, with reported correlations between 0.7 and 0.8, depending on PTA definitions and study group characteristics (Smits et al, 2004; Jansen et al, 2010; Watson et al, 2012; Koole et al, 2016; Potgieter et al, 2018b). As a consequence, high sensitivity and specificity values of >80% to detect hearing impairment have been obtained when appropriate pass/fail criteria are used (Smits et al, 2004; Watson et al, 2012; Jansen et al, 2013; Vlaming et al, 2014; Koole et al, 2016; Folmer et al, 2017; Potgieter et al, 2018a; Vercammen et al, 2018; Potgieter et al, 2018b). Their feasibility as an automatic self-test, robustness to ambient noise levels outside of audiometric booth environments, and low

linguistic (Warzybok et al, 2015; Kaandorp et al, 2016) and cognitive demands have contributed to widespread use for hearing screening.

In adults, the test takes about 3 to 4 minutes to perform. Next to aiming at the shortest test duration possible, achieving high reliability or a low measurement error is important with respect to screening test efficiency. More precisely, the ratio between the standard deviation of SRTs between participants and the measurement error should be as high as possible.

Efforts have been made by researchers to improve the efficiency of existing DTTs by experimenting with test modifications that would result in a larger spread of SRTs among participants. Especially the use of alternative maskers has been explored to sensitize the test for the detection of (high-frequency) hearing impairment (after Leensen et al, 2011): e.g. using fluctuating (Smits & Houtgast, 2007) or low-pass filtered (Vlaming et al, 2014; Vercammen et al, 2018) rather than continuous broadband speech-shaped noise that is spectrally identical to the speech material.

These modifications have improved the correlation between SRTs and PTAs, and because of their improved sensitivity for high-frequency hearing impairment, speech-in-noise screening tests using low-pass filtered rather than broadband noise are being commonly used, e.g. for the detection of noise-induced hearing impairment in the framework of occupational healthcare (Leensen & Dreschler, 2013; Sheikh Rashid et al, 2017; Jansen et al, 2014), but also targeting adolescents for whom concerns regarding recreational noise-induced hearing impairment are growing (Rashid et al, 2016). Inconsistent findings have been published with respect to the reliability of such tests, with some suggesting no impact of using low-pass filtered noise on test reliability (Leensen et al, 2011), and some suggesting a decrease in reliability (Jansen et al, 2014; Vlaming et al, 2014).

When properly homogenized speech materials are used, test-retest reliability for currently available DTTs is well below 1 dB, reflecting a steeply sloped psychometric curve. This is relevant for emerging longitudinal hearing research using DTTs (Pronk et al, 2013; Pronk et al, 2014; Stam et al, 2015; Stam et al, 2016), as well as for hearing screening programs that intend to follow-up on hearing over time (Denys et al, 2018).

Less research has been devoted to increasing DTTs' test-retest reliability to improve test efficiency. Hence, this study aimed at investigating test modifications that might increase test-retest reliability. In particular, the use of variable adaptive step sizes according to a digit scoring method was explored. Usually, the presentation level is adapted per trial with a fixed step size of 2 dB based on the response for a complete triplet; i.e. the SNR is decreased in case of a correctly identified triplet (the test becomes more difficult), and increased in case of an incorrect triplet response (the test becomes easier). For matrix tests, presenting syntactically fixed but semantically unpredictable sentences in noise constructed from an underlying word matrix of ten names, verbs, numerals, adjectives and nouns, adaptive step sizes that depend on the number of correctly identified words per trial are used, and this has resulted in an improved reliability of the obtained SRTs (Brand & Kollmeier, 2002). This principle might also be applicable to DTTs if the step size is varied according to the number of individual digits per triplet that are recognized correctly.

Generally, the probability to recognize a digit correctly p , i.e. the recognition probability, is linked to the steps S_i (in dB) for i correctly recognized digits by the weighted sum of the probability mass function of the binomial distribution

$$\sum_{i=0}^3 S_i \binom{3}{i} p^i (1-p)^{3-i} = 0 \quad (1)$$

For triplet scoring, using equal adaptive steps of $S = 2$ dB, results in an average recognition probability of approximately 79% for a single digit. Indeed, the 50% recognition probability for a triplet is the product of the recognition probabilities of 79% for individual digits (p^3). For digit scoring, the step size depends on the number of correctly recognized digits i . Here, the steps are linearly spaced across the same range as used for triplet scoring, i.e. $2S = 4$ dB, which for a given recognition probability p results in a step size

$$S_i = 2S \left(p - \frac{i}{3} \right) \quad (2)$$

As such, by simply adjusting the adaptive step size depending on the number of digits correctly identified, any recognition probability desired can be targeted, and a DTT using digit scoring can be parametrized to target the same recognition probability as a DTT with triplet scoring, i.e. 79%, resulting in similar SRTs. Importantly, modifications applied to the baseline DTT (i.e. the original test) should not affect its validity in terms of the correlation between the SRT and the PTA. Also, in order to reach improved efficiency (by increasing test-retest reliability), the spread in SRTs among individuals, which can also be expressed in terms of the SRT-PTA correlation, should remain unaltered.

As a first study aim, it was investigated whether a DTT using low-pass filtered noise would result in equal or worse test-retest reliability as compared to the baseline DTT with broadband speech-shaped noise, and whether an improved SRT-PTA correlation could be achieved.

A second aim of this study was to investigate whether using a digit scoring procedure would result in increased test-retest reliability compared to the baseline DTT, without affecting its correlation with the PTA. Also, an evaluation of DTT procedures

131 targeting other recognition probabilities, i.e. 57% and 35%, in comparison to the
132 commonly used recognition probability of 79%, in terms of test-retest reliability and
133 agreement with the PTA was conducted.

Materials and methods

Participants

In total, 68 participants (34 female, 34 male) participated in the experiment. Participants with all air-conduction thresholds better than or equal to 20 dB HL were defined as normal hearing and served as a reference group, resulting in 23 normal hearing (NH) participants. The other 45 participants were assigned to the hearing impaired (HI) group and had varying degrees of hearing impairment (Figure 1). NH participants were between 17 and 61 years (median age: 22 years, interquartile range: 27 years), and HI participants were between 18 and 71 years (median age: 59 years, interquartile range: 12 years). All participants took part voluntarily and signed an informed consent form. The study was approved by the medical ethical committee of the University Hospitals Leuven.

Methodology

General study procedures and materials

Per participant, all data were obtained in one session of about one hour. The tests were conducted in a quiet room. Audiograms were obtained for both ears, followed by multiple DTTs in the better ear.

Pure tone air- and bone- conduction thresholds were measured at octave frequencies from 250 Hz to 8 kHz according to the 5-up 10-down Hughson-Westlake method (Carhart and Jerger, 1959) with masking according to the method of Hood (Hood, 1960) if required. A Madsen Midimate 622 audiometer was used, connected to TDH-39 headphones and a B71 bone vibrator, calibrated according to ISO standards.

Next, 11 DTTs were performed by every participant in the better ear: one bilateral (diotic) training test with 12 trials, and a test and retest of the 5 DTT conditions described

below, in random order. The tests were conducted on 7 inch Google Nexus tablets, connected to DD45 transducers embedded in Peltor caps, calibrated to the test noise at 80 dB SPL.

Identical instructions were given prior to each test by means of an instruction screen. Participants were instructed to respond with 3 digits, with the response buttons for 7 [ze:vən], 9 [ne:gən] and 0 [nʏl] disabled, and could respond during stimulus presentation. They completed the tests without supervision of the test leader. Regular pauses were held in order to avoid fatigue.

Digit Triplet Test conditions

Five different conditions were investigated, using the speech and noise material described in more detail in the *Appendix*. The names of the procedures consist of a letter denoting the type of scoring (T and D for triplet and digit scoring, respectively), the recognition probability or target point for a single digit, and an optional suffix LP for the test condition using a low-pass filtered noise, e.g. T79LP or D50. The specific parameter settings are summarized in Table 1 and Figure 2. Except for the training test with 12 trials, each test consisted of 27 triplets in speech-shaped noise, presented monaurally (to the better ear). One of 10 balanced test lists was randomly chosen, and triplets were presented in random order. For each test, the SRT was calculated by averaging the SNRs of the last 21 triplets presented, plus the SNR of a virtual (non-presented) 28th triplet. The first six triplets were not used for the SRT calculation.

Triplet scoring procedure (T79). Procedure T79 is the baseline procedure as described in Jansen et al. (2013). Digit triplets were presented in a continuous broadband speech-shaped noise masker that is spectrally identical to the speech material used, fixed at 65 dB SPL. A simple up-down adaptive procedure was used, varying the speech level with fixed steps of 2 dB according to the identification response for a whole triplet (triplet

scoring), i.e. all three digits needed to be identified correctly to decrease the SNR. The first triplet was presented at an SNR of 0 dB. Digits had been equated for intelligibility in this type of noise (Jansen et al, 2013). A test with the same parameters was also used for training, but was presented bilaterally with only 12 (instead of 27) trials.

Triplet scoring procedure with low-pass filtered noise. Procedure T79LP also used triplet scoring and a simple up-down adaptive procedure. The original background noise was replaced by a low-pass filtered version, and digits had been equated for intelligibility in this type of noise (*Appendix*). To compensate for the attenuation effect of the low-pass filter, a fixed noise level of 75 dB SPL was used. The initial step size was twice as large as for the baseline procedure T79 to provide the required rapid descent to reach the proximity of the SRT for NH participants within the first 6 triplets not used for the SRT calculation.

Digit scoring procedures targeting different recognition probabilities. Procedures D79, D57 and D35 again used the broadband noise of the baseline procedure T79, fixed at 65 dB SPL. Adaptive step sizes depending on the number of correctly recognized digits were used (digit scoring), parametrized to converge to recognition probabilities of 79, 57 and 35% (equation 2). To provide the same rate of descent as for the baseline procedure, a recognition probability of 50% was used for the first 6 trials. To allow for the correct association of presented and recognized digit, feedback about the position of the presented digit was provided by highlighting the corresponding response field.

Statistical analysis

Statistical calculations were performed using the R software environment (version 3.2.3) for statistical computing and graphics (R Core Team, 2015).

The influence of background noise type and scoring method (for procedures targeting a recognition probability of 79%), and the influence of recognition probability (for digit scoring procedures) on the SRT was investigated, both for all and only NH participants. For each procedure, mean SRTs were calculated per participant by averaging test- and retest-SRTs. When multiple factors were involved, the effect of each independent factor was analysed with random-effects ANOVAs. Normality of individual variables was checked by Shapiro-Wilk tests. For normally distributed variables, within- or between-subject effects were tested with paired or unpaired Student's t-tests, respectively. Otherwise, Wilcoxon signed-rank or Mann-Whitney U tests were used.

Test-retest errors (TRTE) were calculated to estimate the reliability of the DTT, i.e. the deviation of test results from the underlying actual threshold. Individual TRTEs were calculated per participant and DTT condition as the signed sample-based standard deviation. Across participants, e.g. for the NH and HI groups, the TRTE was calculated as the standard deviation of the individual TRTEs (Smits & Houtgast, 2007). This definition results in a TRTE estimate that has the same variability as the difference between estimated and underlying actual threshold. To evaluate test-retest reliability, the absolute deviation from the median was calculated as a robust measure of variability. Significant differences in variability with respect to type of background noise and scoring method used (for procedures targeting a recognition probability of 79%), as well as the recognition probability targeted (for digit scoring procedures) were tested with Wilcoxon signed-rank tests.

SRTs were compared to the PTA calculated from the average audiometric threshold at 1, 2 and 4 kHz. Pearson correlation coefficients between PTA and SRT were calculated per procedure after averaging test- and retest-SRTs per participant. Significance was tested for positive association for all participants, and separately for NH

230 and HI participants. For the 79% recognition probability, the influence of background
231 noise and scoring method was analysed. For the digit scoring procedures, the influence
232 of the recognition probability was investigated. Significant differences for two dependent
233 correlations sharing one variable were tested with a two-tailed Williams's Test.
234 Dependent correlations with no shared variables were tested with a two-tailed Steiger
235 Test. To control the family-wise error rate for multiple comparisons, the Holm-
236 Bonferroni method was used.

237 Bootstrapping with $n = 1000$ iterations was used to calculate 95% confidence
238 intervals.

Results

Speech Reception Thresholds

Figure 3 shows the distribution of SRTs per procedure for HI and NH participants. Across all participants, for procedures targeting a recognition probability of 79%, mean SRTs from T79LP were 9.6 dB lower (better) than from T79, and no significant difference was found between D79 and T79 ($p < 0.001$ and $p > 0.05$, respectively). For the digit scoring procedures, mean SRTs from D79 were 2 dB higher (worse) than from D57, which were in turn 2.3 dB higher than those of D35 ($p < 0.001$).

For NH participants, mean SRTs from T79LP were about 13.3 dB lower than from T79, and no significant difference was found between D79 and T79 ($p < 0.001$ and $p > 0.05$, respectively). For the digit scoring procedures, mean SRTs from D79 were 1.5 dB higher than from D57, which were in turn 1.9 dB higher than those of D35 ($p < 0.001$).

Test-retest reliability

Table 2 shows the TRTEs for the different procedures for NH and HI participants. Across all procedures, TRTEs in HI participants were 0.19 dB higher than in NH participants (95% CI [0.09-0.29] dB, $p < 0.001$). With digit scoring procedure D79, TRTEs were significantly lower by 0.19 dB compared to triplet scoring procedure T79 (95% CI [0.02-0.36] dB, $p < 0.05$). No significant difference in test-retest reliability was observed for T79 and T79LP ($p > 0.05$).

SRT-PTA correlations

Figure 4 shows scatterplots of the SRT versus PTA. All correlations between PTA and SRT were significant when tested for all participants and only HI participants, but none for only NH participants ($p < 0.001$ and $p > 0.05$, respectively). When comparing

262 correlations for the different methods using a 79% recognition probability, i.e. T79,
263 T79LP and D79, no significant differences were found ($p < 0.05$), both neither for all
264 participants (mean $r = 0.90$) nor for only HI participants (mean $r = 0.86$). When comparing
265 correlations for the digit scoring procedures at different recognition probabilities (D79,
266 D57 and D35,) D79 yielded better scores than D57 and D35, and D57 better than D35
267 ($p < 0.05$), both for all participants as well as for only HI participants.

Discussion

This study investigated modifications of the DTT in order to improve its efficiency. The use of a low-pass filtered noise as well as the use of variable adaptive step sizes according to a digit scoring procedure were explored. These modifications were hypothesized to either increase the spread in SRTs among participants (low-pass filtered noise) or increase test-retest reliability (digit scoring), leading to improved test efficiency.

Baseline procedure

For the baseline procedure T79, SRTs for the NH participants were very similar to the mean SRT of -11.7 dB SNR reported for the same material in Jansen et al. (2013). Also, test-retest reliability was similar to values previously reported for the Flemish DTT (Jansen et al, 2013; Jansen et al, 2014) and DTTs for other languages. Test-retest reliability was lower in HI participants, which might have been caused by the shallower slopes of their psychometric curves. Post-hoc psychometric curve fitting indeed showed a decrease in slope of 1.3%/dB per dB increase in SRT, as is also reported in the literature (Smits & Houtgast, 2005; Smits & Houtgast, 2006; Smits & Festen, 2011). PTA and SRT were highly positively correlated when calculated for all participants, with correlation coefficients being in line with reported values between 0.7 and 0.8 (Smits et al, 2004; Jansen et al, 2010; Watson et al, 2012; Koole et al, 2016; Potgieter et al, 2018b). The declining correlation when only including HI listeners is smaller than the 0.28 seen for the French DTT in Jansen et al. (2012), which might be because of the more loose criterion for HI participants in that study. For only NH participants, the SRTs were not sufficiently sensitive to detect differences in PTAs. This was expected given the strict definition of normal hearing with all air-conduction thresholds better than or equal to 20 dB HL.

Low-pass filtered noise procedure

For T79LP, SRTs for the NH participants agreed with the mean SRT of -24.6 dB SNR obtained in its development experiment (Appendix). As expected, SRTs for the low-pass filtered noise procedure decreased and were more variable when compared to T79, i.e. SRTs were more spread out for the HI participants depending on their high frequency audiometric threshold (Leensen et al, 2011; Jansen et al, 2014; Vlaming et al, 2014). No significant difference in test-retest reliability was observed for T79LP and T79. This is in accordance with the results of Leensen et al. (2011) for Dutch CVC words. Correlations between SRTs and PTAs for both procedures were around 0.9 and did also not differ between procedures, presumably because correlations for T79 were already high. These results suggest that the use of a low-pass filtered noise would not result in improved test efficiency, which is in contrast to findings reported by other researchers, who reported increases in absolute correlations when switching from a broadband to a low-pass filtered noise using English digit triplets (from 0.62 to 0.79: Vlaming et al, 2014), or Dutch (from 0.75 to 0.91: Leensen et al, 2011), Flemish (from 0.64 to 0.79: Jansen et al, 2014) and French (from 0.73 to 0.91: Jansen et al, 2014) CVC words.

To investigate whether the use of a low-pass filtered noise might nevertheless capture additional information about hearing impairment, linear modelling was used to predict T79LP-SRTs from T79-SRTs and pure tone thresholds. In a first model with only the T79-SRT as predictor, T79LP-SRTs could be predicted with an R^2 of 86.6% ($p < 0.001$). Using the Akaike Information Criterion (AIC), pure tone thresholds were included step-wise to obtain the best fit possible with as few variables as possible. This resulted in a second model that included pure tone thresholds at 0.5 and 2 kHz, which significantly increased the proportion of explained variance to 92.3% ($p < 0.001$). This indicates that the low-pass filtered noise procedure captured additional information about

the pure tone thresholds that is not captured by T79. Most likely, the thresholds at 0.5 and 2 kHz provided the necessary information on the amount and slope of high-frequency hearing impairment. The remaining unexplained variance might be rather independent of hearing impairment and could be dominated by random effects, such as measurement error.

Digit scoring procedures

Digit scoring allowed for the use of different recognition probabilities, resulting in different SRTs. SRTs for D79 did not differ significantly from T79. For lower recognition probabilities, SRT variability decreased, similar to what has been reported by Smits & Houtgast, 2007. This can be related to the effect of hearing impairment on the parameters of the psychometric curve. With increasing hearing impairment, the psychometric curve is not so much shifted to higher SNRs, but actually p anchored as chance level is approached. In this way, both midpoint (SRT) and slope are affected. Therefore, for participants with different hearing impairment degrees, the variability of the upper-right part of the curve will be higher than in the lower part (Smits & Festen, 2011; Smits & Festen, 2013).

Digit scoring procedure D79 resulted in significantly higher test-retest reliability compared to T79. This is most probably due to the increase in the number of effective stimuli used for D79 psychometric curve calculations and the SNRs used for the SRT calculation being distributed more evenly and closer to the recognition probability, which is in agreement with the results for matrix sentence tests (Brand & Kollmeier, 2002). On the other hand, SRT-PTA correlations for procedures D79 and T79 did not differ significantly, indicating improved test efficiency.

Lower recognition probabilities resulted in lower test-retest reliability. This could have been caused by the larger ratio of accidentally correct answers relative to the expected recognition probabilities. This is in agreement with simulations done by Smits & Festen (2011). In their study, the most reliable recognition probability for shallow slopes of the psychometric curve was found to be around 80%. Also, correlations between PTAs and SRTs for lower recognition probabilities decreased, which might have been partially caused by the higher measurement errors.

Implications and future research perspectives

Altogether, using a recognition probability of 79% seems valid, and a better choice than using lower probabilities. The use of variable adaptive step sizes according to a digit scoring method improves test efficiency due to an increased test reliability, and, therefore, yields a more efficient test than does triplet scoring with a fixed step size. Relative to the reliability of the currently used Flemish DTT, test-retest reliability increased by 0.2 dB. Conveniently, SRTs remain unaltered avoiding the need to establish new normative values or pass/fail-criteria. However, its performance should be re-evaluated in a larger study sample for further validation, especially in terms of its sensitivity and specificity to detect hearing impairment, e.g. in the context of occupational or school health hearing screening.

Also, with respect to test efficiency, so far, test duration has not been taken into account. Nevertheless, hearing screening tests are best kept as short as possible to have optimal cost-efficiency. Whereas test duration can simply be reduced by presenting fewer triplets or trials, such a reduction will result in a loss of reliability. Under the assumption of independence of the individual responses, test reliability is expected to decrease with the number of trials n used for the SRT calculation, i.e. $TRTE \sim \sqrt{n}^{-1}$. However, given

the increased test-retest reliability using digit scoring, a similar TRTE as for T79 would already be reached after 17 triplets for D79, corresponding to a reduction in triplets of 37%. Such a test would then be as efficient as the currently used DTT with triplet scoring and 27 trials, provided that its correlation with the PTA remains unchanged. To simulate a shorter test with a total number of 17 triplets, the SRTs for D79 were recalculated from the SNRs of triplets 12 to 23. This resulted in a TRTE of 0.86 dB and an SRT-PTA correlation of 0.92. Such a shorter test should be evaluated in future research regarding its reliability and validity, especially in the light of possible attention effects because of the changed number of triplets (Witton et al, 2017). Indisputably, screening programs using the DTT might benefit from a shorter test, especially when targeting children who have limited attention spans. In Flanders, where the DTT is used for school-age hearing screening (Denys et al, 2018; Guérin et al, 2018), test durations of about 6 to 7 minutes have been reported for 3rd grade elementary and 5th grade secondary school children, which can be considered rather long for screening. More importantly, attention loss during the test, resulting in poor SRTs, might add to the proportion of unjustified referrals. One way to minimize this, could be the use of a shorter (and hence more efficient) test. Recently, a fixed SNR procedure was introduced, in which the average number of presentations needed was only 30 to 50% of the number of presentations used for an adaptive procedure, whilst having equal pass and refer rates (Smits, 2017).

Importantly, especially when using faster procedures that use fewer triplets, optimal convergence to the SRT within the first 6 trials not used for its calculation, should be obtained. The initial recognition probability for the digit scoring procedures evaluated in this study was set to 50%, as digit scoring for the 79% recognition probability would have led to a slow descent (the maximum step size = 0.83 dB). The speed of convergence for all procedures was investigated (Figure 5). Depending on the procedure, the SNR of

389 a certain number of triplets differed significantly from the SRT ($p < 0.05$). For the triplet
390 scoring procedures T79 and T79LP, convergence was achieved within the initial 6 triplets
391 allocated for descent. For the digit scoring procedures, only D57 converged properly, with
392 significant differences from the SRT up to the 11th and 10th triplet for procedures D79 and
393 D35, respectively. While procedure D35 undershot the SRT at the 7th triplet with about
394 2.4 dB on average, procedure D79 exhibited a mean overshoot of about 1.7 dB that took
395 several triplets to recover. This was worse for HI participants. For the 79% recognition
396 probability, a procedure which would use triplet scoring during the initial descent (the
397 first 5 triplets) and digit scoring for the remaining triplets might be a possible solution.
398 Such a procedure should be evaluated in future studies using the DTT with digit scoring,
399 albeit with 27 or 17 trials.

Conclusion

This study aimed to improve the efficiency of the Flemish DTT. The use of a low-pass filtered noise did not result in an improved SRT-PTA correlation or increased reliability. Using digit scoring with variable adaptive step sizes parametrized to target a recognition probability of 79% improved test-retest reliability. This procedure should be further evaluated with respect to its sensitivity and specificity to detect hearing impairment, the more because it offers opportunities to reduce the number of trials (and hence test duration), which would be beneficial for large-scale screening programs in which the test is already being used. Targeting lower recognition probabilities decreased test-retest reliability, as well as correlations with the PTA and should not be used.

Appendix

In this appendix, we describe the optimization of the DTT speech material for use in low-pass filtered noise, and its evaluation in NH participants.

The speech and noise material of the Flemish DT as described in Jansen et al. (2013) was used. This material consists of 10 balanced lists of 27 digit triplets each, with digits equated for intelligibility in broadband speech-shaped noise. Only the monosyllabic digits 1 [e:n], 2 [twe:], 3 [dri:], 4 [vi:r], 5 [vɛif], 6 [zɛs] and 8 [axt] are used, which were recorded by a professional female native Flemish speaker, and concatenated into digit triplets. Per list, every digit occurs 3 to 4 times at every position in the triplet. Digits have a common length of 601 ms and are presented with gaps of 200 ms between them. The original broadband speech-shaped background noise was replaced by a low-pass filtered version, as described in Jansen et al. (2014). It consists of the sum of the speech-shaped noise, low-pass filtered at 1.4 kHz with a roll-off slope of more than 100 dB per octave, and the original speech-shaped noise attenuated by 15 dB. The noise starts 1 s before and stopped 500 ms after each triplet, and has a 50 ms fade using a Hann window.

Stimuli were played back using APEX 3 software (Francart et al, 2008; Francart et al, 2017), installed on a Dell Latitude D510 laptop, routed through an external Fireface UCX soundcard connected to Sennheiser HDA-200 headphones and presented monaurally to the best ear. Responses were typed in by the participants using a numerical touch pad connected to the laptop.

Six NH adults (thresholds at all octave frequencies ≤ 15 dB HL, confirmed by standard pure tone audiometry) participated in the optimization experiment. Following a training list at -18 dB SNR, test lists were presented at several fixed SNRs, ranging from -22 to -30 dB SNR in steps of 2 dB relative to a fixed noise level of 65 dB SPL. Per SNR, 2 test lists were presented, and test lists used were balanced among participants.

Responses were scored at the level of individual digits. Per digit, a psychometric curve was fitted using equation (3). The level of individual digits was adjusted by the difference in SRT for the individual digit and the average SRT for all digits, to obtain equated intelligibility and a homogenous test material with a steeply sloped psychometric curve. This was done to obtain the highest possible test reliability. Level corrections performed ranged from -1.6 to 1.2 dB, but were generally < 1 dB.

Twelve NH participants participated in the evaluation experiment. Here, reference values were determined for the test at adaptively varying as well as at fixed SNRs. Per participant, first, 11 tests lists (including 1 list for training) were performed adaptively with a start-SNR of -18 dB and a fixed step size of 2 dB, followed by 4x3 test lists at fixed SNRs of -22, -23.5, -25 and -26.5 dB, relative to a noise level of 75 dB SPL. Test lists were again presented with balanced order. Responses were now scored at the level of triplets. Per participant, a psychometric curve was fitted to the data obtained at fixed SNRs, again using equation (3). This resulted in a reference curve with a slope of 21.5%/dB (as opposed to 17.5%/dB prior to optimization) and a reference-SRT ± 2 SD of -25.1 ± 1.6 dB SNR. When fitted per list, SRTs fell within a range of 1 dB of the reference-SRT. For the adaptive procedure, SRTs were determined by averaging the SNRs of the last 21 presented triplets and a 28th non-presented triplet for which the SNR was calculated from the response for the lastly presented triplet. This resulted in a reference-value ± 2 SD of -24.6 ± 1.4 dB SNR. The reliability of the SRT-estimate was calculated by taking the root mean square of the SDs across repeated tests per participant, and was 0.7 dB.

References

- Akeroyd, M.A., Arlinger, S., Bentler, R.A., Boothroyd, A., Dillier, N., et al, 2015. International Collegium of Rehabilitative Audiology (ICRA) recommendations for the construction of multilingual speech tests. *International journal of audiology*, 54(sup2), p.17–22.
- Brand, T., Kollmeier, B., 2002. Efficient adaptive procedures for threshold and concurrent slope estimates for psychophysics and speech intelligibility tests. *The Journal of the Acoustical Society of America*, 111(6), p.2801–2810.
- Denys, S., Hofmann, M., Luts, H., Guerin, C., Keymeulen, A., et al, 2018. School-Age Hearing Screening Based on Speech-in-Noise Perception Using the Digit Triplet Test. *Ear and hearing*, 39(6), p.1104–1115.
- Folmer, R.L., Vachhani, J., Mcmillan, G.P., Kidd, G.R., Feeney, M.P., 2017. Validation of a Computer-Administered Version of the Digits-in-Noise Test for Hearing Screening in the United States. *Journal of the American Academy of Audiology*, 28(2), p.161–169.
- Francart, T., Hofmann, M., Vanthornhout, J., Van Deun, L., van Wieringen, A., et al, 2017. APEX/SPIN: a free test platform to measure speech intelligibility. *International journal of audiology*, 56(2), p.137–143.
- Francart, T., van Wieringen, A., Wouters, J., 2008. APEX 3: a multi-purpose test platform for auditory psychophysical experiments. *Journal of Neuroscience Methods*, 172, p.283–293.
- Guérin, C., Van Hoeck, K., Denys, S., van Wieringen, A., Wouters, J., et al, 2018. Systematische opsporing van lawaaischade bij jongeren. *JGZ Tijdschrift voor Jeugdgezondheidszorg*, 50(5-6), p.132–137.
- Jansen, S., Luts, H., Dejonckere, P., van Wieringen, A., Wouters, J., 2013. Efficient hearing screening in noise-exposed listeners using the digit triplet test. *Ear and hearing*, 34(6), p.773–778.
- Jansen, S., Luts, H., Dejonckere, P., van Wieringen, A., Wouters, J., 2014. Exploring the sensitivity of speech-in-noise tests for noise-induced hearing loss. *International journal of audiology*, 53(3), p.199–205.
- Jansen, S., Luts, H., Wagener, K.C., Frachet, B., Wouters, J., 2010. The French digit triplet test: a hearing screening tool for speech intelligibility in noise. *International journal of audiology*, 49(5), p.378–387.
- Jansen, S., Luts, H., Wagener, K.C., Kollmeier, B., Del Rio, M., et al, 2012. Comparison of three types of French speech-in-noise tests: a multi-center study. *International journal of audiology*, 51(3), p.164–173.

- 493 Koole, A., Nagtegaal, A.P., Homans, N.C., Hofman, A., Baatenburg de Jong, R.J., et al,
494 2016. Using the Digits-In-Noise Test to Estimate Age-Related Hearing Loss. *Ear*
495 *and hearing*, 37, p.508–513.
- 496 Leensen, M.C.J., Dreschler, W. a, 2013. The applicability of a speech-in-noise
497 screening test in occupational hearing conservation. *International journal of*
498 *audiology*, 52(7), p.455–65.
- 499 Leensen, M.C.J., de Laat, J. a P.M., Snik, A.F.M., Dreschler, W. a, 2011. Speech-in-
500 noise screening tests by internet, part 2: improving test sensitivity for noise-
501 induced hearing loss. *International journal of audiology*, 50(11), p.835–48.
- 502 Potgieter, J.-M., Swanepoel, D.W., Myburgh, H.C., Hopper, T.C., Smits, C., 2015.
503 Development and validation of a smartphone-based digits-in-noise hearing test
504 in South African English. *International journal of audiology*, 55(7), p.405–411.
- 505 Potgieter, J.-M., Swanepoel, D.W., Myburgh, H.C., Smits, C., 2018a. The South
506 African English Smartphone Digits-in-Noise Hearing Test: Effect of Age, Hearing
507 Loss, and Speaking Competence. *Ear and hearing*, 39(4), p.656–663.
- 508 Potgieter, J.-M., Swanepoel, D.W., Smits, C., 2018b. Evaluating a smartphone digits-in-
509 noise test as part of the audiometric test battery. *The South African journal of*
510 *communication disorders = Die Suid-Afrikaanse tydskrif vir*
511 *Kommunikasieafwykings*, 65(1), p.e1–e6.
- 512 Pronk, M., Deeg, D.J.H., Festen, J.M., Twisk, J.W., Smits, C., et al, 2013. Decline in
513 older persons' ability to recognize speech in noise: the influence of demographic,
514 health-related, environmental, and cognitive factors. *Ear and hearing*, 34(6),
515 p.722–732.
- 516 Pronk, M., Deeg, D.J.H., Smits, C., Twisk, J.W., van Tilburg, T.G., et al, 2014. Hearing
517 Loss in Older Persons: Does the Rate of Decline Affect Psychosocial Health?
518 *Journal of aging and health*, 26(5), p.703–723.
- 519 Rashid, M.S., Leensen, M.C.J., Dreschler, W.A., 2016. Application of the online
520 hearing screening test “Earcheck”: Speech intelligibility in noise in teenagers and
521 young adults. *Noise and Health*, 18, p.312–318.
- 522 Sheikh Rashid, M., Leensen, M.C., de Laat, J.A., Dreschler, W.A., 2017. Cross-
523 sectional evaluation of an internet-based hearing screening test in an occupational
524 setting. *Scandinavian journal of work, environment & health*, 43(3), p.279–286.
- 525 Smits, C., 2017. Improving the Efficiency of Speech-In-Noise Hearing Screening Tests.
526 *Ear and hearing*, 38(6), p.e385–e388.
- 527 Smits, C., Festen, J.M., 2013. The interpretation of speech reception threshold data in
528 normal-hearing and hearing-impaired listeners: II. Fluctuating noise. *The Journal*
529 *of the Acoustical Society of America*, 133(5), p.3004–15.

- 530 Smits, C., Festen, J.M., 2011. The interpretation of speech reception threshold data in
531 normal-hearing and hearing-impaired listeners: steady-state noise. *The Journal of*
532 *the Acoustical Society of America*, 130(5), p.2987–98.
- 533 Smits, C., Houtgast, T., 2006. Measurements and calculations on the simple up-down
534 adaptive procedure for speech-in-noise tests. *The Journal of the Acoustical Society*
535 *of America*, 120(3), p.1608–21.
- 536 Smits, C., Houtgast, T., 2007. Recognition of digits in different types of noise by
537 normal-hearing and hearing-impaired listeners. *International journal of audiology*,
538 46(3), p.134–44.
- 539 Smits, C., Houtgast, T., 2005. Results from the Dutch speech-in-noise screening test by
540 telephone. *Ear and hearing*, 26(1), p.89–95.
- 541 Smits, C., Kapteyn, T.S., Houtgast, T., 2004. Development and validation of an
542 automatic speech-in-noise screening test by telephone. *International journal of*
543 *audiology*, 43(1), p.15–28.
- 544 Smits, C., Merkus, P., Houtgast, T., 2006. How we do it: The Dutch functional hearing-
545 screening tests by telephone and internet. *Clinical otolaryngology*, 31(5), p.436–
546 440.
- 547 De Sousa, K.C., Swanepoel, D.W., Moore, D.R., Smits, C., 2018. A Smartphone
548 National Hearing Test: Performance and Characteristics of Users. *American*
549 *journal of audiology*, 27(3S), p.448–454.
- 550 Stam, M., Smit, J.H., Twisk, J.W.R., Lemke, U., Smits, C., et al, 2016. Change in
551 Psychosocial Health Status Over 5 Years in Relation to Adults' Hearing Ability in
552 Noise. *Ear and hearing*, 37(6), p.680–689.
- 553 Stam, M., Smits, C., Twisk, J.W.R., Lemke, U., Festen, J.M., et al, 2015. Deterioration
554 of Speech Recognition Ability Over a Period of 5 Years in Adults Ages 18 to 70
555 Years : Results of the Dutch Online Speech-in-Noise Test. , p.129–137.
- 556 Vercammen, C., Goossens, T., Wouters, J., van Wieringen, A., 2018. Digit Triplet Test
557 Hearing Screening With Broadband and Low-Pass Filtered Noise in a Middle-
558 Aged Population. *Ear and hearing*, 39(4), p.825–828.
- 559 Vlaming, M.S.M.G., MacKinnon, R.C., Jansen, M., Moore, D.R., 2014. Automated
560 Screening for High-Frequency Hearing Loss. *Ear and hearing*, p.1–13.
- 561 Watson, C.S., Kidd, G.R., Miller, J.D., Smits, C., Humes, L.E., 2012. Telephone
562 screening tests for functionally impaired hearing: current use in seven countries
563 and development of a US version. *Journal of the American Academy of Audiology*,
564 23(10), p.757–767.
- 565 Willberg, T., Buschermohle, M., Sivonen, V., Aarnisalo, A.A., Lopponen, H., et al,
566 2016. The development and evaluation of the Finnish digit triplet test. *Acta oto-*
567 *laryngologica*, 136(10), p.1035–1040.

- 568 Witton, C., Talcott, J.B., Henning, G.B., 2017. Psychophysical measurements in
569 children : challenges , pitfalls , and considerations. *PeerJ*, 5, p.e3231.
- 570 Zokoll, M. a, Wagener, K.C., Brand, T., Buschermöhle, M., Kollmeier, B., 2012.
571 Internationally comparable screening tests for listening in noise in several
572 European languages: the German digit triplet test as an optimization prototype.
573 *International journal of audiology*, 51(9), p.697–707.
- 574 Zokoll, M.A., Hochmuth, S., Warzybok, A., Wagener, K.C., Buschermohle, M., et al,
575 2013. Speech-in-noise tests for multilingual hearing screening and diagnostics1.
576 *American journal of audiology*, 22(1), p.175–178.
- 577

Figures and Tables

Figure 1. Distribution of the pure tone thresholds (in dB HL) per frequency (in Hz) for hearing impaired (HI, left panel) and normal hearing (NH, right panel) participants. Each black line represents a different percentile.

Figure 2. Step sizes (in dB) according to the number of correctly recognized digits per triplet for the different Digit Triplet Test procedures for the triplets assigned to the initial descent (upper row) and for the remaining triplets (lower row).

Figure 3. Distribution of speech reception thresholds (SRT, in dB SNR) for the different Digit Triplet Test procedures for hearing impaired (HI, left panel) and normal hearing (NH, right panel) participants.

Figure 4. Scatterplots of the speech reception thresholds (SRT, in dB SNR) versus pure tone averages (PTA, i.e. averaged hearing threshold over frequencies 1-4 kHz, in dB HL) for the different Digit Triplet Test procedures for normal hearing (green dots) and hearing impaired (orange dots) participants. Numerical information on the graphs represent correlation coefficients (r) for all (in black) and only hearing impaired (in orange) participants, with 95% confidence intervals, resulting from basic bootstrapping with $n=1000$ iterations. Dotted lines represent linear regression fits.

Figure 5. Convergence plots for the different Digit Triplet Test procedures for hearing impaired (HI, upper row) and normal hearing (NH, lower row) participants. Red boxes indicate triplets at which the SNR is significantly different from the speech reception threshold (SRT), which lies at 0 dB signal-to-noise ratio (SNR). The vertical black dotted lines divide each plot in descending (or convergence) trials and trials used for the calculation of the SRT.

Table 1. Parameter settings for the different Digit Triplet Test procedures used.

Table 2. Test-retest errors for the different Digit Triplet Test procedures used for hearing impaired (HI) and normal hearing (NH) participants. Values between brackets indicate 95% confidence intervals, resulting from basic bootstrapping with $n=1000$ iterations.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

615

Table 1

Procedure	Scoring	Masker	Masker level	Feedback	Start-SNR	<i>p</i> ₁₋₆	<i>p</i> ₇₋₂₈
			(dB SPL)		(dB)	(%)	(%)
T79	Triplet	Broadband	65	No	0	79	79
T79LP	Triplet	Low-pass	75	No	-2	79	79
D79	Digit	Broadband	65	Yes	-2	50	79
D57	Digit	Broadband	65	Yes	-2	50	57
D35	Digit	Broadband	65	Yes	-2	50	35

616

617

Table 2

Procedure	HI	NH
T79	1.02 [0.85-1.22]	0.62 [0.45-0.82]
T79LP	0.96 [0.76-1.20]	0.63 [0.47-0.83]
D79	0.76 [0.61-0.93]	0.45 [0.32-0.58]
D57	0.72 [0.57-0.89]	0.51 [0.42-0.64]
D35	0.87 [0.69-1.08]	0.76 [0.54-1.02]

618