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The Dichotic Digits difference Test (DDdT): Development, Normative Data and Test-Retest Reliability Studies

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Abstract

Background: The dichotic digits test is one of the most widely used assessment tools for central auditory processing disorder (CAPD). However, questions remain concerning the impact of cognitive factors on test results.

Purpose: To develop the Dichotic Digits difference Test (DDdT), an assessment tool which could differentiate children with cognitive deficits from children with genuine dichotic deficits based on differential test results. The DDdT consists of four subtests: dichotic free recall (FR), dichotic directed left ear (DLE), dichotic directed right ear (DRE), and diotic. Scores for six conditions are calculated (free recall LE, RE and total, as well as DLE, DRE and diotic). Scores for four difference measures are also calculated: Dichotic Advantage, Right Ear Advantage (REA) FR, REA Directed and Attention Advantage.

Research Design: Experiment 1 involved development of the DDdT, including error rate analysis. Experiment 2 involved collection of normative and test-retest reliability data.

Study Sample: Twenty adults (25, 10 (yr, mo) to 50, 7, mean 36, 4) took part in the development study; 62 normal-hearing, non-clinical, primary-school children (7, 1 (yr, mo) to 11, 11, mean 9, 4) and ten adults (25, 0 (yr, mo) to 51, 6, mean 34, 10) took part in the normative and test-retest reliability study.

Data Collection and Analysis: In Experiment 1 error rate analysis was conducted on the 36 digit pair combinations of the DDdT. Normative data collected in Experiment 2 was arcsine transformed to achieve a distribution that was closer to a normal distribution and z-scores calculated. Pearson product-moment correlations were utilized to determine the strength of relationships between DDdT conditions.

Results: The development study revealed no significant differences in the adult population between test and retest on any DDdT condition. Error rates on 36 digit pairs ranged from 1.5% to 16.7%. The most and least error-prone digits were removed prior to commencement of the normative data study, leaving 25 unique digit pairs. Average z-scores calculated from the arcsine-transformed data collected from the 62 children who took part in the normative data study revealed that free recall dichotic processing (LE, RE and total) was highly correlated with diotic processing (r ranging from 0.5 to 0.6; $p < 0.0001$). Significant improvements in performance on retest occurred for the FR LE, RE, total and diotic conditions (p ranging from 0.05 to 0.0004), the conditions that would be expected to improve with practice if the participant's response strategies are better the second time around.

Conclusions: The addition of a diotic control task - that shares many response demands with the usual dichotic tasks - opens up the possibility of differentiating children who perform below expectations because of poor dichotic processing skills from those who perform poorly because of impaired attention, memory, or other cognitive abilities. The high correlation between dichotic and diotic performance suggests that factors other than dichotic performance play a substantial role in a child's ability to perform a dichotic listening task. This hypothesis will be investigated further in the cognitive correlation study presented in Cameron et al. (in press).

Key Words: Dichotic, diotic, free recall, directed; impulsivity; sustained attention; central auditory processing disorder

Abbreviations: CAPD = Central Auditory Processing Disorder; DDdT = Dichotic Digits difference Test; DLE = directed left ear; DRE = directed right ear; FR = free recall; NAL = National Acoustic Laboratories; REA = right ear advantage; RMS = root mean square.

INTRODUCTION

Although the make-up of central auditory processing test batteries vary widely from clinic to clinic, one of the most common types of tests used are dichotic listening tests (Martin et al, 2007; Schmithorst et al, 2013; Weihing and Atcherson, 2014). Both the American Academy of Audiology (AAA, 2010) and the American Speech and Hearing Association (ASHA, 2005) recommend the inclusion of a dichotic listening task - either dichotic digits, words, or sentences - in the assessment of central auditory processing disorder (CAPD).

Dichotic processing refers to the simultaneous presentation through headphones of different acoustic signals to the left and right ears (Musiek and Weihing, 2011). It is different from diotic processing, in which the same signal is presented to both ears. Clinically, dichotic listening is evaluated using either a free recall task (whereby the patient attends to both ears and repeats back what is heard) or a directed task, whereby the patient is asked to attend to only one ear (Musiek and Weihing, 2011). The free recall task is defined as a measure of binaural integration, whereas the directed task is a measure of binaural separation. For both tasks, results are typically calculated separately as a percentage correct for the left and right ear.

From an anatomical perspective, Musiek and Weihing (2011) explain that the right ear signal will travel directly to the left hemisphere of the cortex via the dominant contralateral pathways, whereas the left ear signal travels to the right hemisphere and then crosses to the left hemisphere via the corpus callosum for processing and verbal response. Thus effective interhemispheric transfer between the two cerebral hemispheres is an important component of dichotic processing. Speech-related stimuli presented to the right ear are typically recalled with greater accuracy than those presented to the left ear (Kimura, 2011; Schmithorst et al, 2013). This right ear advantage (REA) is said to be a consequence of preferential conduction of right-ear messages directly to the typically language-dominant left hemisphere via the stronger contralateral pathways (Hiscock and Kinsbourne, 2011; Kimura, 2011). However, not all left-hemisphere dominant individuals report a REA (Schmithorst et al 2013), and the magnitude of REA has been shown to decrease in older compared with younger children (Moncrieff, 2011). According to Musiek and Weihing (2011) a significant left ear deficit (that is, a relatively *increased* right ear advantage) on dichotic processing tasks is associated with a breakdown in the interhemispheric transfer function at the level of the corpus callosum.

Bellis (2003) suggests that binaural integration and separation processes are reported to be critical to everyday listening. Deficits in these areas, as measured by free recall and directed dichotic tests, may be expressed behaviorally as difficulty hearing in background noise or when more than one person is talking at the same time. Given the reported potential behavioral consequences of dichotic deficits, assessment certainly seems warranted.

However, DeBonis (2015) notes that whereas dichotic tests have been included in auditory processing batteries for over four decades, research has now established that performance on dichotic listening tasks is greatly influenced by allocation of attentional resources. In a review of clinical and experimental evidence concerning dichotic listening studies of hemispheric asymmetry, Westerhausen and Hugdahl (2008), concluded that the corpus callosum is not only a channel for the automatic exchange of information between the cerebral hemispheres, but also allows for dynamic and flexible interaction that supports both bottom-up and top-down processing of auditory stimuli. That is, dichotic processing involves a built-in, automated (or stimulus-driven) component which favors the processing of right ear input, as well as a cognitive (instruction-driven) component that allows for modulation of the laterality effect. To this end, Hiscock and Kinsbourne (2011) state that REA effects cannot be explained on the basis of hypothetical conduction properties of specific auditory pathways, but instead in terms of dynamic processes, including those in which individuals deliberately direct their attention in different ways. As such, the authors conclude that the role of attention is essential for interpreting the process of REA.

In a discussion of resource allocation theory, Bellis (2014) points out, that individuals with higher-order attention, cognitive or related deficits may exhibit decreased performance in tests of fundamental sensory processing due to the extra allocation of effort necessary to attend to, comprehend or remember the stimulus. To this end, Ahmmed et al (2014) reported that in a sample of 110 children with suspected CAPD, performance on a dichotic free recall word test correlated significantly with performance on tests of forward and reverse digit span ($r = 0.34$, $p < 0.01$), and auditory attention cued ($r = 0.30$, $p < 0.01$) and non-cued ($r = 0.23$, $p < 0.05$), but not with non-verbal IQ ($r = -0.03$). Similarly, in a sample of 36 children with suspected CAPD, Maerlender (2010) found a significant correlation between dichotic free recall left ear and digit span forward ($r = 0.68$, $p < 0.001$) and reversed ($r = 0.45$, $p < 0.01$), as well as free recall right ear and digit span forward ($r = 0.38$, $p = 0.02$) and reversed ($r = 0.40$, $p = 0.01$). The author concluded that verbal memory may be a pervasive deficit in children with CAPD, and the value and role of psychometric testing in children suspected of this disorder are supported. It seems more appropriate, however, to conclude that verbal memory deficit may be pervasive in children for whom an assessment for CAPD is sought.

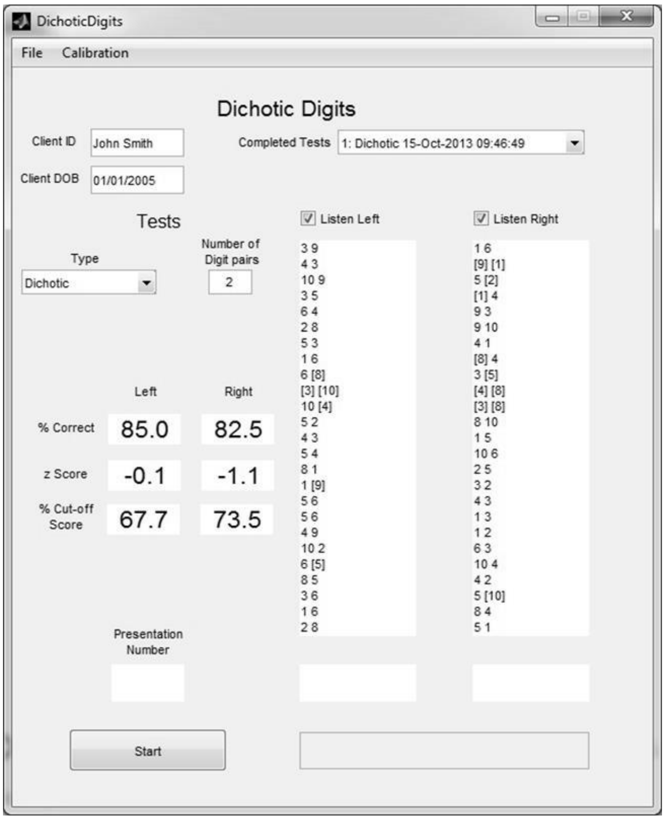
In an investigation of links between auditory processing test results, functional deficits and cognitive abilities in a sample of 50 control and 105 children referred for auditory processing assessment, Tomlin et al (2015) found that both left and right ear free recall dichotic digit test scores correlated significantly ($p \leq 0.01$) with forward and reverse digit span and non-verbal IQ, as well as with attention ($p \leq 0.01$ for left ear and $p \leq 0.05$ for right ear). Multiple regression analysis found that auditory working memory was a significant predictor of dichotic left and right ear performance (β = 0.42, $p < 0.001$; and β = 0.24, $p < 0.01$ respectively) and that non-verbal IQ was a significant predictor of left ear free recall performance (β = 0.58, $p < 0.01$). Tomlin et al (2015) concluded that interpretation of auditory processing tests requires consideration of how cognitive ability may have impacted both test results and the functional difficulties experienced by the child.

The aim of the present study was to develop a test that could be used clinically to identify children with true dichotic processing deficits from those with other deficits which may account for poor dichotic free recall and/or directed performance. The Dichotic Digits difference Test (DDdT; Cameron et al, 2013) utilizes a diotic control condition and measurement of difference scores to alert clinicians to a potential impact of higher order deficits on test performance. The DDdT scoring is highly automated as described in the Methods section to follow. This paper – part one of two on the evaluation of the DDdT – will report on error analysis of digit pairs during the development phase of the study, as well as provide normative and test-retest reliability data in a pediatric and adult population. Correlations between DDdT condition scores are also investigated. The companion paper (Cameron et al., submitted) will investigate correlations between DDdT conditions and measures of cognitive ability (attention, memory and intelligence) as well as measures of real life listening ability.

EXPERIMENT 1 – ADULT DEVELOPMENT STUDY

DDdT Software Development

The DDdT graphical user interface and signal processing application were developed in MATLAB programing language (MathWorks, 2013). An image of the user interface is shown in Figure 1. The monosyllabic digits 1, 2, 3, 4, 5, 6, 8, 9 and 10 were recorded in an anechoic chamber at the National Acoustic Laboratories (NAL). The stimuli were voiced by an adult male with an Australian English accent. Each number was spoken twice in a normal clear voice. The better of the two recordings for each digit, as judged subjectively by two of the authors, were then edited to remove extraneous silence from the beginning and end of each file. This resulted in files with an average length of 631 ms. Each digit was level normalized to a mean root mean square (RMS) level of -25 dB re full digital level to ensure no clipping occurred during playback. To calibrate the software a 1 kHz calibration tone with a mean RMS level of -15 dB re full digital level was activated from the playback screen and the volume of the laptop was adjusted until the electrical level of the calibration signal was 18 mV. This resulted in an RMS presentation level of 50 dB (HL) of the digits when presented through Sennheiser HD215 headphones.



Client ID: John Smith
Client DOB: 01/01/2005
Completed Tests: 1: Dichotic 15-Oct-2013 09:46:49
Type: Dichotic
Number of Digit pairs: 2

	Left	Right
% Correct	85.0	82.5
z Score	-0.1	-1.1
% Cut-off Score	67.7	73.5

☑ Listen Left	☑ Listen Right
3 9	1 6
4 3	[9] [1]
10 9	5 [2]
3 5	[1] 4
6 4	9 3
2 8	9 10
5 3	4 1
1 6	[8] 4
6 [8]	3 [5]
[3] [10]	[4] [8]
10 [4]	[3] [8]
5 2	8 10
4 3	1 5
5 4	10 6
8 1	2 5
1 [9]	3 2
5 6	4 3
5 6	1 3
4 9	1 2
10 2	6 3
6 [5]	10 4
8 5	4 2
3 6	5 [10]
1 6	8 4
2 8	5 1

Figure 1. DDdT graphical user interface (research version).

Method

Approval for the study was granted from the Australian Hearing Human Research Ethics Committee.

Participants

Twenty adults with normal hearing, defined as equal to or better than 20 dB HL at all octave frequencies between 250 Hz and 8000 Hz, were recruited to participate in the study. Participants were aged 25, 10 (yr, mo) to 50, 7 (mean 36, 4) and had no reported history of learning or attention disorders. There were five males and fifteen females. All participants spoke English as their first language. Thirteen participants were retested between 14 days and 31 days after their initial appointment to investigate test-retest reliability.

Procedure

Testing was conducted in a sound-attenuated booth at the National Acoustic Laboratories and took approximately 30 minutes to complete. Pure-tone audiometric screening was performed using a Maico MA 53 clinical audiometer with circumaural Sennheiser HDA 200 audiometric headphones.

The DDdT was administered with the use of a laptop computer and Senheisser HD215 headphones. Sound levels were calibrated prior to each appointment, using the procedure described above. The four subtests of the DDdT (free recall (FR), directed left ear (DLE), directed right ear (DRE) and diotic) were counterbalanced among participants. Five practice trials and twenty scored trials were presented in each subtest and the participants' task varied depending on the subtest. Each trial consisted of four randomly selected digits presented as temporally overlapped pairs. The four subtests were presented, as described below, resulting in six conditions, which were scored as percent correct:

a) Dichotic Free Recall (FR LE, FR RE and FR Total): a set of two numbers were presented to the left ear (e.g. 8, 6) at the same time as two *different* numbers were presented to the right ear (e.g. 1, 3). The digits presented first to each ear overlapped in time, as did the digits presented second to each ear. Participants were asked to repeat back all four numbers in any order (e.g. 6, 8, 1, 3). The LE and RE were scored separately. The average of the LE and RE scores – referred to as FR Total - was also calculated.

b) Dichotic directed LE (DLE): Presentation of stimuli was as per Dichotic FR described above. However, participants were asked to repeat back only the digit pair heard in the left ear (e.g. 8, 6) in any order.

c) Dichotic directed RE (DRE): As for DLE, however, participants were asked to repeat back only the digit pair heard in the right ear (e.g. 1, 3) in any order.

d) Diotic: A set of two numbers (e.g. 8, 1) that were overlapping exactly in time, were presented to both ears. This was followed by another set of two numbers (e.g. 6, 3), that were also overlapping exactly in time, and were also presented to both ears. This resulted in 4 digits in total presented to both ears. Participants were asked to repeat back all four digits in any order.

Results

Statistical Analysis was performed using Statistica Version 10 and Excel 2013.

Analysis for effects of order

A mixed-effects logistics regression model was fitted to the data to determine the effects of test order on condition score. The results indicated that, when averaged across the various DDdT conditions, test scores increased with increased position in test order, with position 3 and 4 significantly higher than position 1 ($p = 0.3$ and 0.01 respectively). When merged across test orders, Friedman ANOVA revealed that the mean score in the diotic condition (96.1%) was significantly lower (p = 0.02) than in the dichotic FR Total condition (97.9%). There were no other significant differences between any other combination of mean scores (FR LE 97.3%; FR RE 98.6%; DLE 98.l%; DRE 98.9%). Inter-subject variation ranged from 2.1 standard deviations (SD) on DRE and FR RE to 3.9 SD on the dichotic condition.

Error Rates Analysis

To determine whether all pair combinations were equally difficult error rates were analysed from the DDdT free recall and diotic results. Figure 2 shows the percentage of presentations in which an error was made for each of the 36 pair combinations, collapsed across conditions. The average error rate was 6.15%, but the error rate for individual pairs varied from 1.5% to 16.7%.

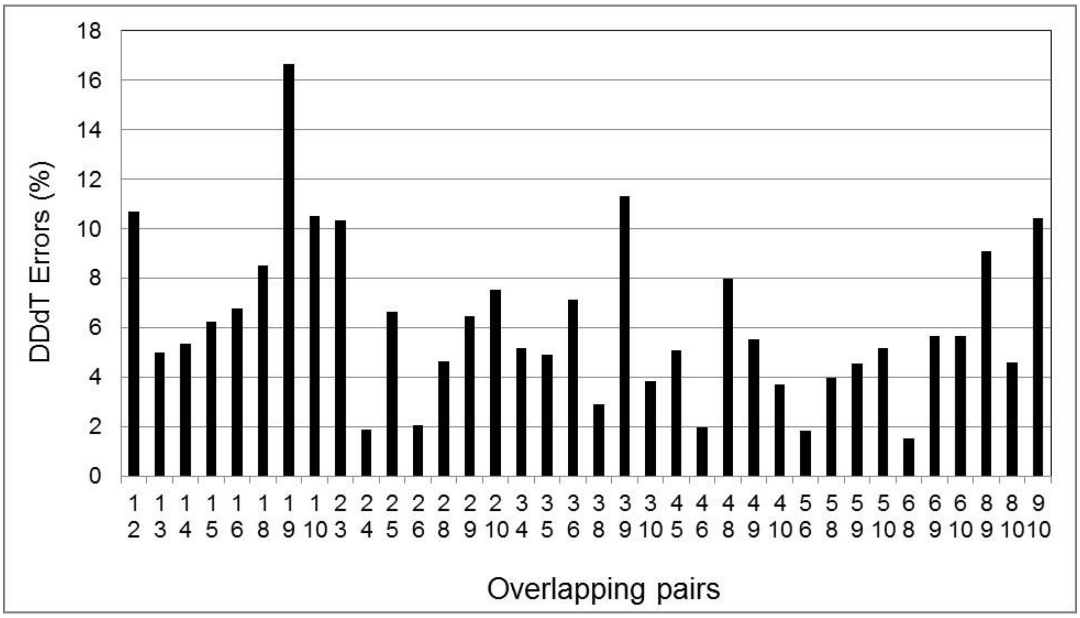


Figure 2. Percent of incorrect response for each digit pair combination for the 20 adults in the development study.

Test-Retest Reliability Analysis

Repeated measures ANOVA revealed that there were no significant differences between test and retest on any of the DDdT test scores (p ranging from 0.08 to 0.83). Any small differences in performance by the 13 adults who took part in the test-retest reliability study were in the direction of improvement at retest. The largest improvement on retest occurred in the diotic condition, where performance improved on average from 96.7% correct at test to 98.1% correct at retest.

*Modifications to Test Based on Result*s

Given that the dichotic free recall scores are higher than the diotic score it appears that dichotic presentation facilitates the understanding of temporally overlapped digits. Given this, it was determined that further research with the DDdT to ascertain its value as a clinical tool for differentiating memory or attention deficits from dichotic deficits was warranted. However, to ensure that each time the test was used with a different random set of digit pairs, the level of difficulty remained constant it was necessary to remove digit pairs which were likely to be markedly easier or more difficult than the remaining pairs. To this end the five most error prone and six least error prone number combinations (1/2, 1/9, 2/4, 2/6, 3/8, 3/9, 4/10, 5/6, 6/8, 8/9, & 9/10) were removed. This left 25 permitted digit pairs. A new random sampling rule was implemented in which each test condition would contain all permitted digit pairs appearing twice within the 25 trials (5 practice and 20 scored). Given the difficulty level of the permitted pairs is approximately equal, the pairs are allowed to appear in either the practice or scored position. Once these changes were implemented an adult normative data study was completed. Further, based on the analysis for effects of order and condition, DDdT conditions were presented in a fixed order (FR, DLE, DRE and diotic) in the normative data study described below.

EXPERIMENT 2 – NORMATIVE DATA AND TEST-RETEST RELIABILITY STUDY

Method

Approval for the study was granted from the Australian Hearing Human Research Ethics Committee and the Catholic Schools Office, Diocese of Broken Bay.

Participants

A total of 72 participants took part in the study. There were ten adults aged 25, 0 (yr, mo) to 51, 6 (mean 34, 10), of which three were male and seven were female. Five of the adult participants had previously taken part in the development study described above. For these participants a minimum of twelve months had elapsed between the two studies to minimize the potential impact of previous exposure to the test procedure on results.

There were 62 children aged 7, 1 (yr, mo) to 11, 11 (mean 9, 4) who took part in the study, of which 27 were male and 35 were female. The children were recruited from a Catholic primary school in New South Wales, Australia, with an average Index of Community Socio-Educational Advantage value similar to the national average. All participants spoke English as their first language, had no reported history of diagnosed or suspected learning or attention disorders and had normal hearing, defined as equal to or better than 20 dB HL at all octave frequencies from 250 Hz to 8000 Hz. Thirty children were re-assessed on the DDdT two months after initial testing to determine test-retest reliability.

Procedure

Adults were assessed at NAL as described in Experiment 1 with the exception that the DDdT conditions were no longer counterbalanced, but presented in the following order: free recall (FR), directed left ear (DLE), directed right ear (DRE) and diotic. Children were assessed in a quiet room on the school grounds. Sound levels in the school testing rooms were measured between 45-50 dBA using a Q1362 digital sound level meter. Pure-tone audiometric screening was performed using an Interacoustics Audio Traveller A222 portable audiometer with Telephonics TDH 39P audiometric headphones in H7A Peltor cups. The DDdT was presented to the adults and children as described in Experiment 1.

Results

Statistical Analysis was performed using Statistica Version 10. As the data were percent correct scores, often close to or at 100%, data were arcsine transformed prior to analysis to more closely approximate a normal distribution.

Gender and Age

The effect of gender on performance was examined in the pediatric data. There was no significant difference between males and females on any of the six DDdT conditions, ranging from $F_{(1,60)} = 1.060$, $p = 0.307$ for the Directed LE condition to $F_{(1,60)} = 3.291$, $p = 0.074$ for the diotic condition.

The mean percentage scores for all participants as a function of age group are provided in Table 1. Transformation of the data and analysis of the effects of age are discussed in the following section.

Table 1. Average percent correct scores on the six DDdT conditions as a function of age.

	Age					
	7	8	9	10	11	Adult
FR LE %	79.5	73.2	79.6	88.8	90.6	99.8
FR RE %	88.9	85.0	86.3	91.8	91.7	99.8
FR Total %	84.4	79.1	82.9	90.3	91.1	99.8
DLE %	81.3	86.1	86.5	91.6	94.4	99.8
DRE %	91.6	87.1	91.9	95.0	96.7	99.3
Diotic %	72.1	72.0	77.3	83.2	87.5	96.0

Arcsine Transformation, Regression and Creation of Z-Scores

The normative data collected from 62 children and 10 adults were used to create equations that allow the expression of individual scores in age-corrected population standard deviation units, that is, z-scores. The method described in Tomlin et al (2014) was used. In brief, this comprised arcsine transformation of the scores, non-linear regression of the transformed scores against age, and calculation of the RMS value of the residual deviations from the fitted functions.

The percentage scores for six DDdT conditions - FR LE, FR RE, FR Total (average of LE and RE); DLE, DRE and diotic - were arcsine transformed using equation 1:

$T = \text{sine}^{-1}(\sqrt{p})$ ….1,

where p is the proportion of digits correct and T is the transformed score. These transformed scores were then regressed against age using the exponential formula shown in equation 2:

$T' = a - b.e^{(-age/c)}$ ….2,

where T′ is the estimated value of T and *a*, *b*, and *c* are the coefficients that determine each curve. These three coefficients, respectively determine the asymptotic value applicable to adults, the rate of change with age, and the age above which the effect of age starts to diminish.

The proportion of variance in transformed scores accounted for by the regression varied from 26% for the DRE condition up to 60% for the FR Total condition. The higher proportion of variance accounted for in the case of the FR Total scores likely reflects the smaller error variance in the total scores, due to their being based on twice as many items as for the individual ear scores.

A preliminary fitting indicated that the value of *c* varied from 4.5 years for the DRE condition up to 17.3 years for the FR RE condition. However, because there were no participants with ages between 13 and 25 years, the value of *c* could be varied widely, along with a compensating variation in the values of *a* and *b*, without markedly affecting the fit to the data. Consequently, all six curves were re-fit with *c* fixed at its median value (7.42 years) found across the conditions in the preliminary fitting. The resulting values of *a* and *b* are shown in Table 2.

Because the scores for the adults were close to ceiling, the residual scores (transformed score minus predicted transformed score) were much smaller for the adults than for the children. Because of this difference, and because of small number of adult subjects, further analysis of the residual scores was carried out for the child data only. The squared residual errors were linearly regressed against age. No significant correlations emerged, and the largest correlation was only -0.12. Consequently, the residual error was characterized by its standard deviation (σ), independent of age. These standard deviations are also shown in Table

2. Calculation of z-scores was then carried out in the usual manner, but using transformed scores and predicted scores, rather than raw scores, as shown in Equation 3:

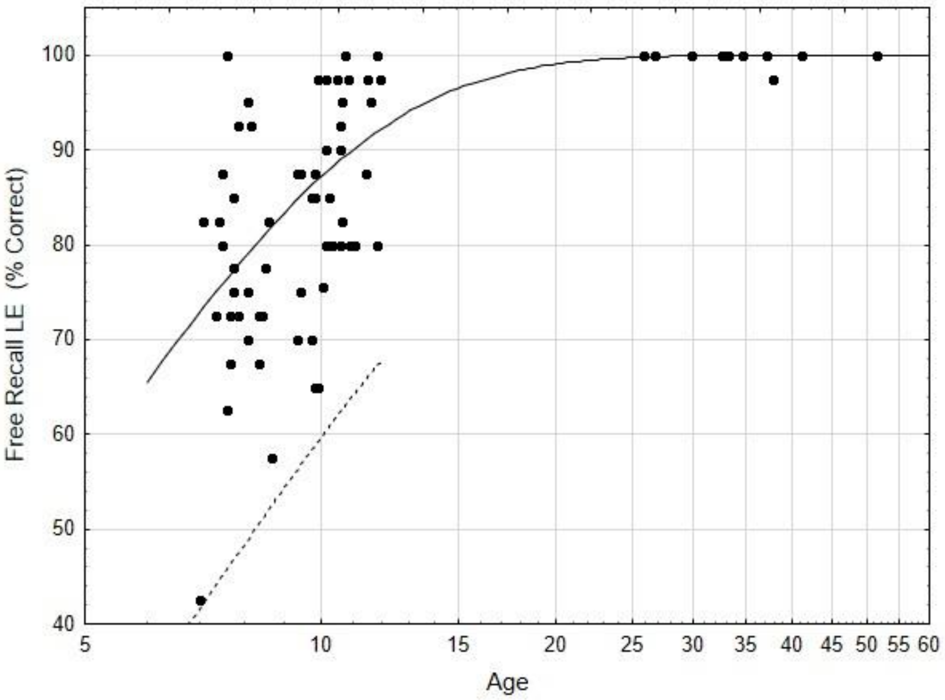
$z = (T - T')/\sigma$ 3,

Table 2. Regression coefficients for the exponential formula shown in Equation 2 ($T' = a - b.e^{(-age/c)}$). Also shown is *σ*, the standard deviation of the residuals (transformed scores minus predicted transformed scores).

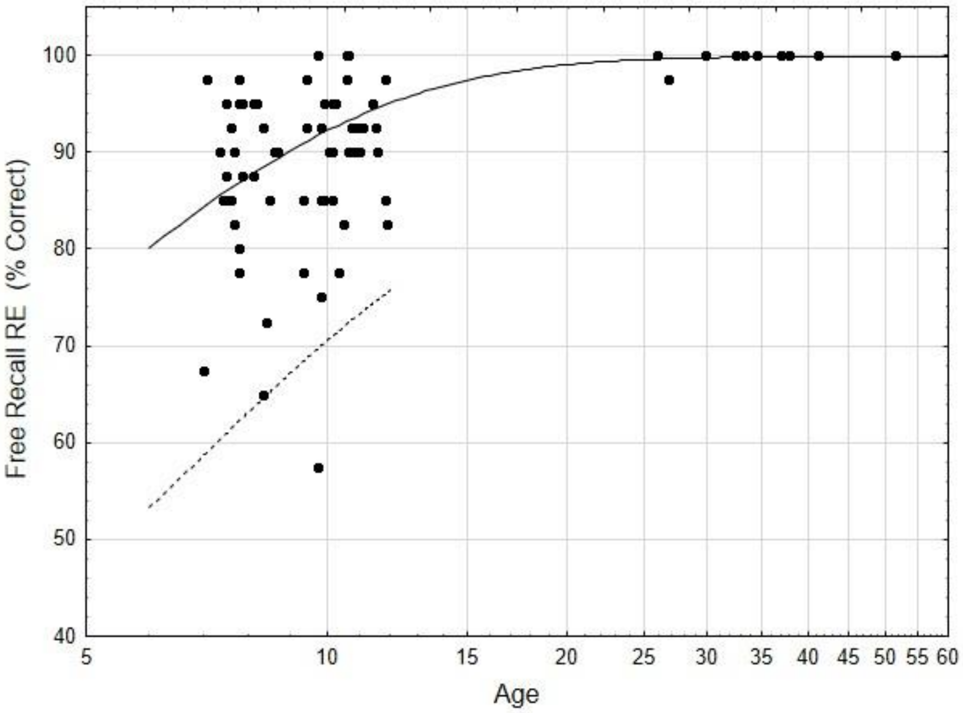
Condition	*a*	*b*	*σ*
FR LE	1.572	1.410	0.160
FR RE	1.542	0.972	0.148
FR Total	1.546	1.201	0.120
DLE	1.581	1.180	0.149
DRE	1.565	0.786	0.161
Diotic	1.440	1.201	0.116

The regression curves (Equation 2) can be inverse transformed back to percentage values (i.e. percent correct) using the inverse of Equation 1. These are shown in Figure 3 (a to f), along with the original data, also in percentage values. Also shown in these graphs are the percentage values that correspond to the transformed values that are two standard deviations below the age-dependent mean values. These are shown only up to age 12 as they are based on the residual values only up to this age.

(a)


Free Recall LE (% Correct)
100
90
80
70
60
50
40
5
10
15
20
25
30
35
40
45
50
55
60
Age

(b)


Free Recall RE (% Correct)
100
90
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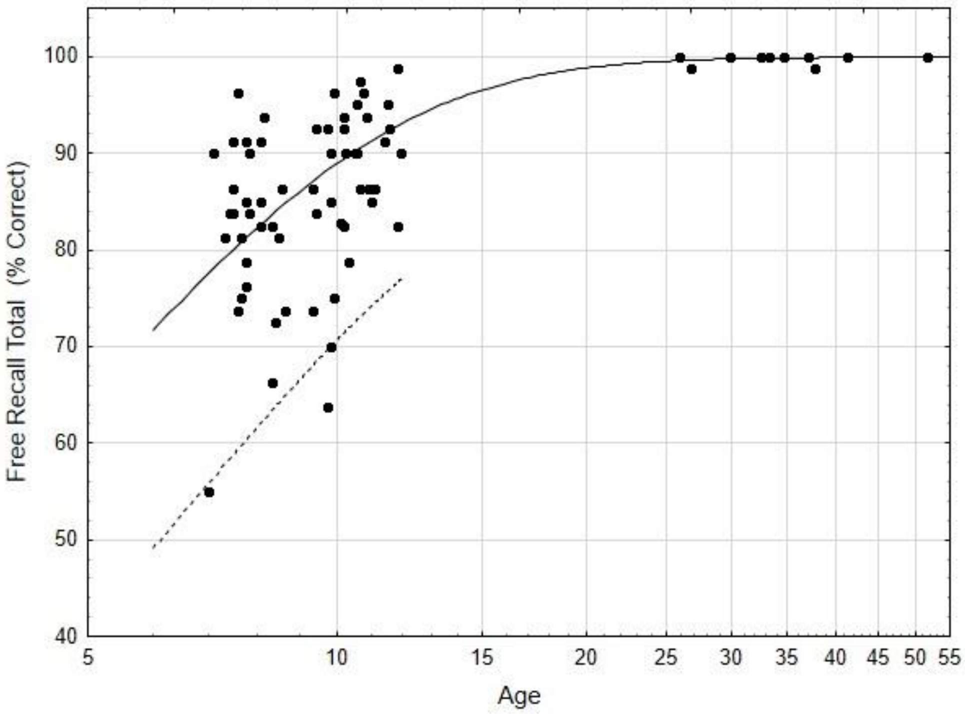
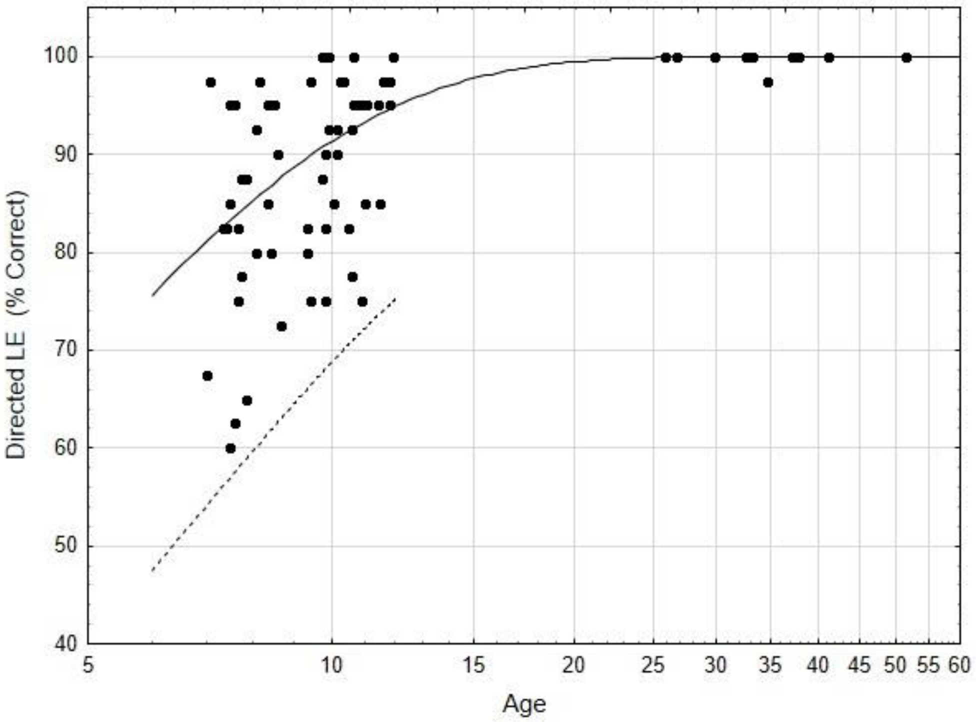
60
Age

(c)


Free Recall Total (% Correct)
40
50
60
70
80
90
100
Age
5
10
15
20
25
30
35
40
45
50
55

(d)


Directed LE (% Correct)
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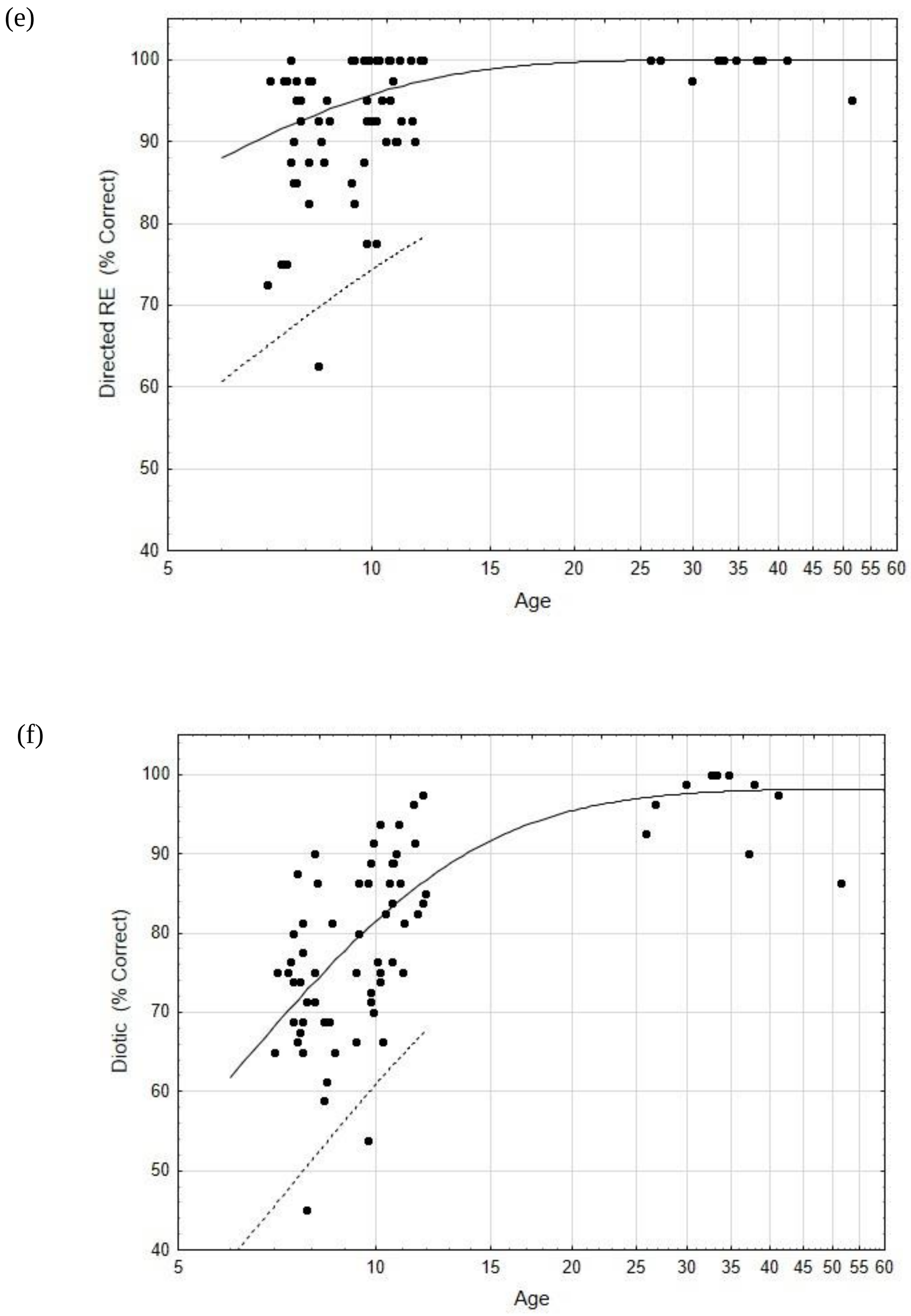


Figure 3. Scatterplots of the untransformed DDdT data and the regression curve (solid line) transformed back to percentage values (i.e. percent correct): (a) FR LE; (b) FR RE; (c) FR Total; (d) DLE; (e) DRE; (f) Diotic, based on the data from the 62 children and 10 adults in

the normative data study. The dashed line represents the percentage values that correspond to the transformed values that are two standard deviations below the age-dependent mean values.

Normality

The z-scores were examined to determine if they deviated significantly from normal distributions. Based on the Shapiro-Wilks test of normality, there was no evidence of a deviation from normality for five of the 6 conditions, with p values ranging from 0.27 to 0.81. The exception was the DRE condition, for which the Shapiro-Wilks W-value was 0.95 and the corresponding p-value was 0.03. The greatest deviation from normality was a greater than expected number of z-scores in the range 1 to 1.5 standard deviations above the mean. These were caused by a number of 9 to 12-year olds all achieving a score of 100% in this condition.

Difference Scores

The data were used to derive the following difference scores, D, between pairs of conditions.

1. Dichotic advantage: Dichotic FR Total score minus diotic score.
2. Right ear advantage (Free Recall): Dichotic FR RE score minus FR LE score.
3. Right ear advantage (Directed): Directed RE score minus Directed LE score.
4. Attention advantage: Average of the Directed RE and LE scores minus FR Total score.

It should be noted that by Attention advantage we refer to the increase in scores that arise when a child has to attend to only one ear at a time. This advantage may arise from avoiding the need to analyze two targets presented simultaneously (as one of the digits becomes only a masker) and/or the reduced load put on memory (as only two digits rather than four must be reported).

Difference Statistics Based on Transformed Data

For each difference score, all of which were computed based on the transformed data (i.e. using Equation 1), the difference score was linearly regressed against age, using just the child data, and the regression coefficients *f* and *g*, as defined in Equation 4 and as shown in Table 3, were found:

$$TD' = f + g.age \quad \ldots. 4,$$

where TD’ is the expected age-appropriate difference in transformed scores. Of the four difference scores, only the right ear advantage score in the free recall condition was significantly correlated with age (r=-0.26, p= 0.04). The standard deviation, σ, of the residual values was computed, enabling z-scores to be calculated as shown in Equation 5, values for which are also shown in Table 3:

$$z = (TD - TD')/ \sigma \quad \ldots. 5.$$

Table 3. Regression coefficients for the equation shown in Equation 4. Also shown is *σ*, the standard deviation of the residuals (difference scores minus predicted difference scores).

Difference score	***f***	***g***	***σ***
Dichotic advantage	0.247	-0.0155	0.101
REA – free recall	0.390	-0.0317	0.173
REA – directed	0.176	-0.0081	0.182
Attention advantage	-0.003	0.0106	0.121

Difference statistics based on original data

Untransformed difference scores (i.e. in percentage points) were also regressed against age, because of the complications in inverse transforming a difference of two arcsine-transformed scores. Equation 6 was fitted to the untransformed data for the children and adults combined:

$$D' = h + i.\exp(-age/j) \quad \ldots. \, 6.$$

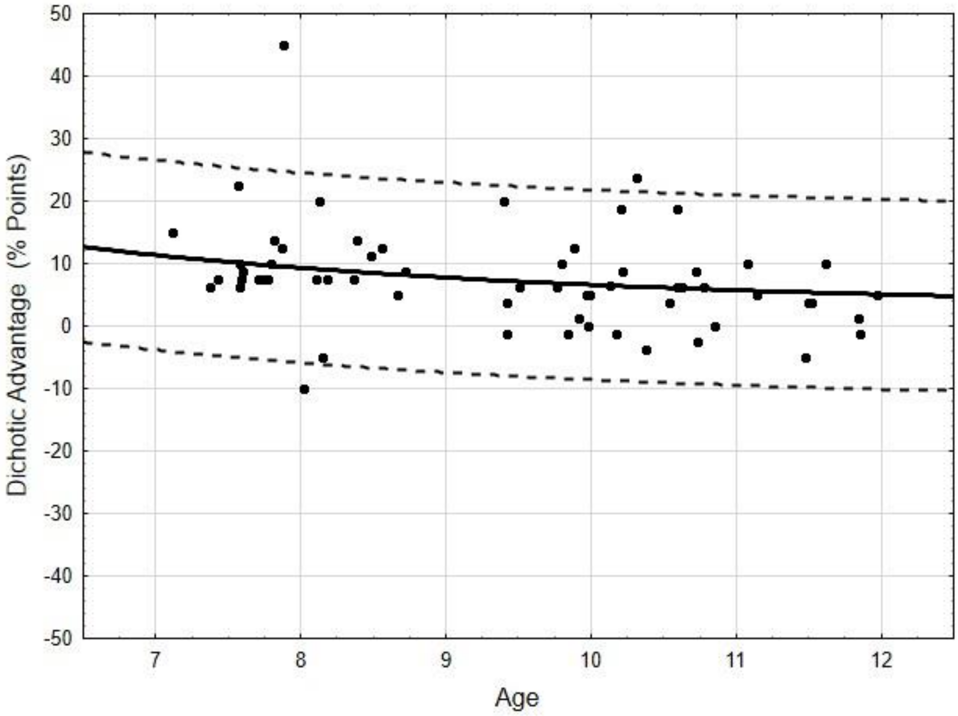
The regression coefficients are shown in the Table 4, along with the standard deviation of the residuals. In the case of the two right-ear advantage measures, the adult data showed a right-ear advantage so close to zero, the *h* parameters were set exactly to zero prior to fitting. In the case of attention advantage, there was no apparent dependence on age, so the *i* parameter was set to zero. In all cases, the standard deviation of the residuals were calculated using only the child data.

Table 4. Regression coefficients for the equation shown in Equation 6. Also shown is σ, the standard deviation of the residuals (difference scores minus predicted difference scores).

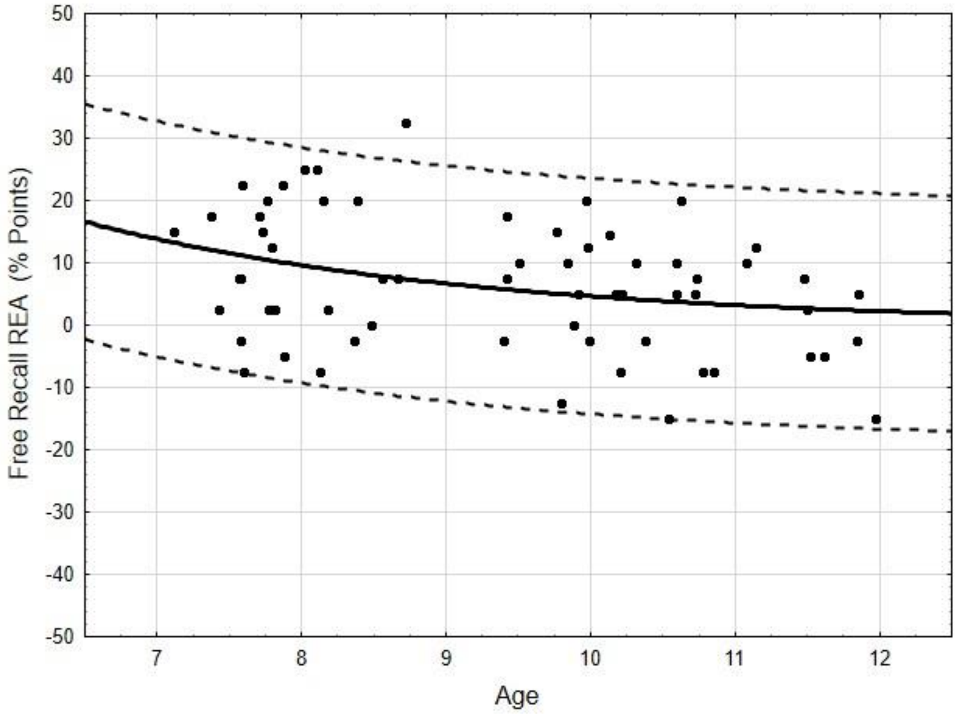
Difference score	***h***	***i***	***j***	**σ**
Dichotic advantage	3.10	61.12	3.50	7.60
Right ear advantage – free recall	0	176.20	2.75	9.45
Right ear advantage – directed	0	50.41	3.91	10.48
Attention advantage	4.43	0	-	7.45

Figure 4 (a to d) shows the means and ± 2 standard deviation (SD) limits for the difference measures as a function of age.

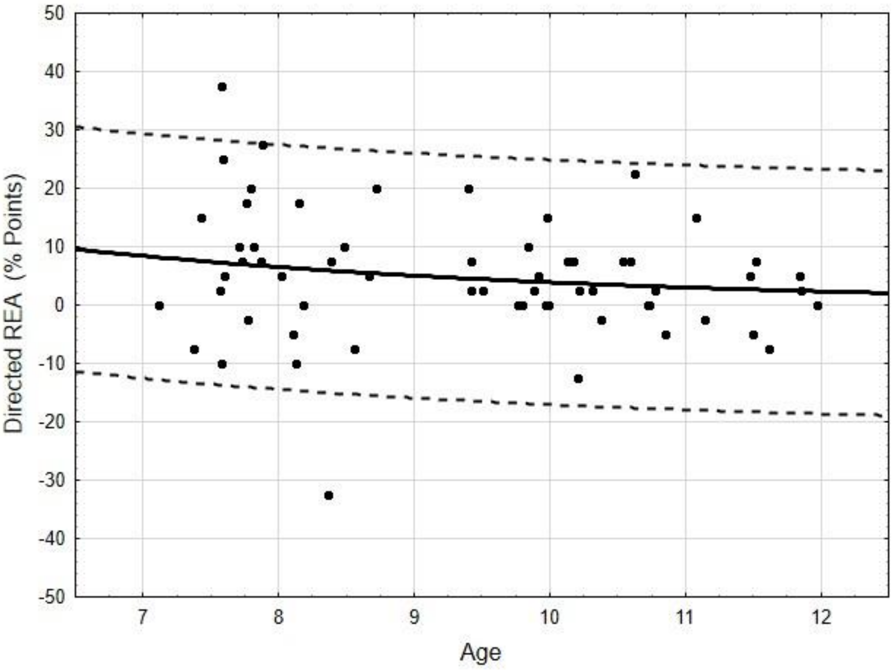
(a)



(b)



(c)



(d)

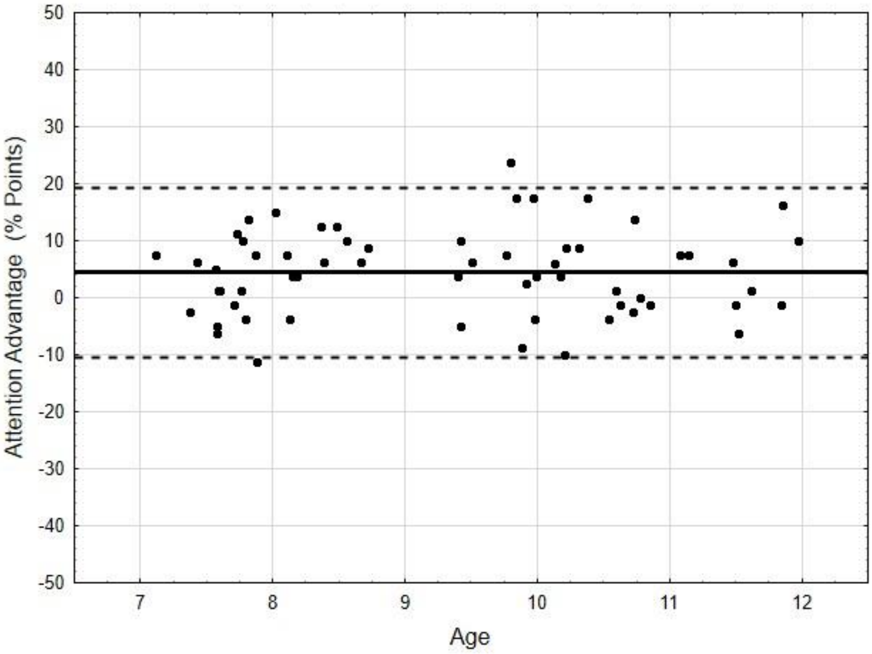


Figure 4. Scatterplots of performance on the DDdT difference measures (Dichotic Advantage, Free Recall REA, Directed REA and Attention Advantage) by the 62 children in the normative data study. The solid line indicates the mean score as a function of age, the dashed lines show the + and – 2 standard deviation limits.

Test-retest Reliability

Repeated measures ANOVAs were performed on the data from the 30 children who took part in the test-retest reliability study. Means, SDs and p values calculated from the transformed z-scores for the six DDdT conditions and four advantage measures are provided in Table 5. The mean differences (retest score minus test score) are also provided, together with the intra-subject variability, which provides a measure of the spread around the change from test to retest.

It was found that dichotic free recall improved significantly with practice (FR LE [$F_{(1,29)} = 4.008$, $p = 0.055$]; FR RE [$F_{(1,29)} = 7.420$, $p = 0.011$]; and FR Total [$F_{(1,29)} = 15.957$, $p = 0.0004$]). The diotic condition also improved significantly with practice ($F_{(1,29)} = 11.212$, $p = 0.002$). However, the directed conditions did not improve significantly with practice (DLE [$F_{(1,29)} = 0.014$, $p = 0.906$] and DRE [$F_{(1,29)} = 0.011$, $p = 0.918$]). Right ear advantage did not improve for either the free recall ($F_{(1,29)} = 0.005$, $p = 0.945$), or directed ($F_{(1,29)} = 0.001$, $p = 0.976$) conditions. Attention advantage decreases somewhat ($F_{(1,29)} = 3.906$, $p = 0.058$), because free recall performance improved with practice but directed performance did not.

Pearson product-moment correlations between DDdT test and retest performance are also provided in Table 5. The largest test-retest correlations were found for the FR Total ($r = 0.72$, $p = 0.00001$) and diotic conditions ($r = 0.71$, $p = 0.00001$).

The second-last column in Table 5 shows the percentage of score variance that likely reflects random measurement error. These were computed as one minus half the square of the test-retest standard deviations (given that the expected value of the total score variance is 1.0 because these are standardized scores, and that both test and retest measurement error contribute to the test-retest standard deviations). The two measurement results with the smallest percentage of measurement error are the FR Total score and diotic score, as each is based on 80 scored items, whereas the other base scores are based on only 40 scored items. The advantage measures generally have a high proportion of measurement error, which is not surprising given that they are based on the difference between two scores.

Table 5. Average test, retest and retest minus test z-scores and SDs for each DDdT condition and advantage measure for the 30 children who took part in the test-retest reliability study. P-values from repeated measures ANOVAs of test and retest z scores and error variance (%) are also provided. Pearson product-moment correlation coefficient (r) is shown, with significant test-retest correlations marked with an asterisk (* < 0.05; ** < 0.01).

	Test	*Retest*	*Retest-Test*				
Condition	*Mean z-score*	*Mean z-score*	*Mean z-score*	*SD*	*p-value*	*Error variance (%)*	*r*
FR LE	-0.08	0.30	0.39	1.06	0.055	56	0.36 *
FR RE	-0.24	0.21	0.44	0.89	0.011	40	0.56 *
FR Total	-0.18	0.33	0.51	0.70	0.0004	25	0.72 **
DLE	-0.18	-0.17	0.02	0.82	0.906	34	0.54 *
DRE	-0.12	-0.10	0.02	1.23	0.918	76	0.07
Diotic	-0.15	0.23	0.38	0.62	0.002	19	0.71 **
Diotic Adv	0.03	0.19	0.16	0.99	0.381	49	0.25
FR REA	-0.09	-0.07	0.02	1.40	0.945	98	-0.03
Directed REA	0.02	0.03	0.01	1.07	0.976	57	0.36 *
Attention Adv	-0.18	-0.68	-0.50	1.37	0.058	94	0.04

DDdT Condition Correlations

Pearson product-moment correlation analysis were used to analyse whether correlations existed between scores on the various DDdT conditions. Due to the ceiling effects in the adult data, the correlations were conducted on the data from the 62 children. Results are provided in Table 6. Note that, statistically it could be expected that within a correlation matrix, one in twenty correlations may be significant by chance alone if an alpha level of 0.05 were to be used. In order to reduce the chance of finding an erroneously significant correlation, only correlations significance at a level of $p < 0.01$ are highlighted.

Table 6. Pearson product-moment correlation coefficient (r), analyzed from the arcsine transformed z scores on the various DDdT conditions, for the 62 children in the normative data study. Significant correlations are marked with an asterisk * < 0.01; ** <0.001).

Condition	FR LE	FR RE	FR Total	DLE	DRE	Diotic
FR LE	1.00	0.37 *	0.87 **	0.36 *	0.28	0.50 **
FR RE		1.00	0.77 **	0.23	0.48 *	0.55 **
FR Total			1.00	0.36	0.43 *	0.62 **
DLE				1.00	0.32	0.32
DRE					1.00	0.35 *
Diotic						1.00

The correlation between the diotic condition and the various free recall conditions were highly significant. FR LE (r = 0.50, p = 0.00004); FR RE (r = 0.55, p < 0.00001) and FR Total (r = 0.62, p < 0.00001), as shown in Figure 5.

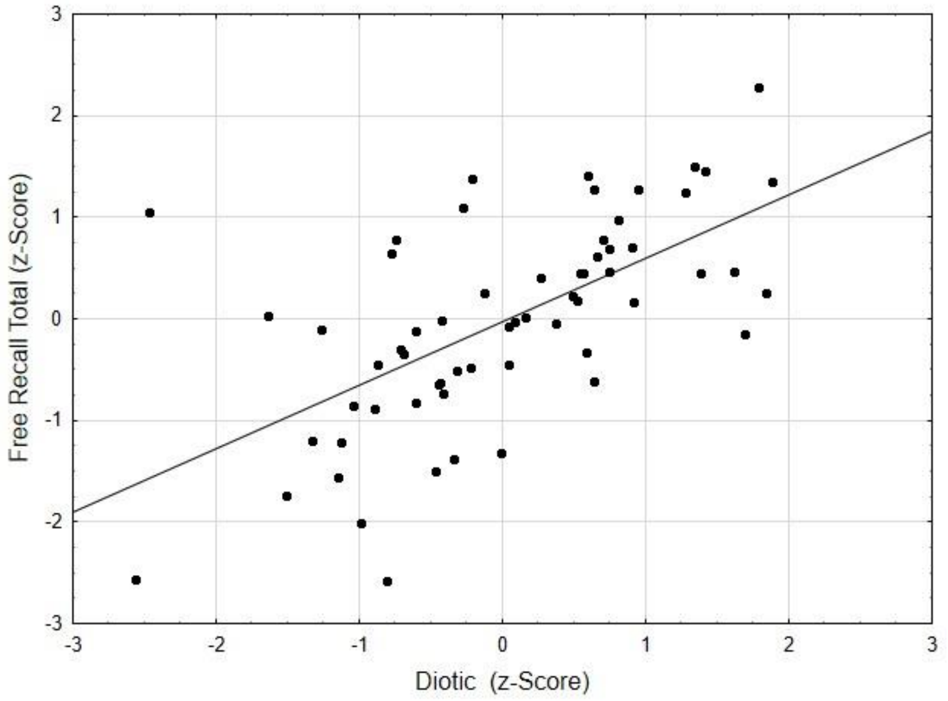


Figure 5. Scatterplot of the DDdT Free Recall Total z-scores compared to the diotic z scores for the 62 children in the normative data study. The solid line represents least squares regression line.

DISCUSSION

The studies presented here involved the development and evaluation of a new dichotic listening test - the Dichotic Digits difference Test (DDdT). The DDdT utilizes automated scoring and reporting features and was designed with the aim of providing clinicians with additional information as to the validity of a dichotic diagnosis, in clients with suspected CAPD, via the inclusion of a diotic control condition which requires the same response criteria and carries the same memory load as the dichotic free recall task. The inclusion of the diotic condition enabled calculation of a *dichotic advantage* score, measured as the average of the free recall (FR) right and left ear scores (referred to as FR total) minus the diotic score. This difference score provides a means of assessing genuine dichotic ability by minimizing the impact of cognitive skills on test score.

However, in evaluating the validity of the dichotic advantage score as a means of assessing genuine dichotic ability, the similarities and differences between the dichotic and diotic conditions should be examined, particularly in respect to the masking properties of the stimuli. In the diotic condition two digits are presented simultaneously to both ears, resulting in within-ear energetic masking that would not occur in the dichotic condition. The energetic masking would make the diotic condition more difficult than the dichotic and this is evidenced by the higher average dichotic compared to diotic scores across age groups shown in Table 1. In contrast, informational masking arises from similarity of the target and masker and this same similarity occurs in both the dichotic and diotic conditions. If informational masking occurs after inputs from the two ears have been combined, as seems likely, it is not expected that there would be any difference in this type of masking between the two conditions, except for any reduction that is enabled by the apparent spatial separation of the two inputs.

Thus it could be said that a poor result (compared to average performance calculated from the normative data) in the dichotic condition may be due to (a) reduced cognitive ability, or (b) reduced dichotic processing ability. By contrast, a poor result in the diotic condition may be due to (a) reduced cognitive ability, or (b) reduced cochlear resolution. It seems unlikely that reduced cochlear resolution would be a significant factor determining performance in children with normal hearing threshold. As such, it is most likely that dichotic advantage score primarily reflects dichotic processing ability.

In a phase one study, stimuli were adjusted for equalization of difficulty based on error-rate analysis. This equalization makes it possible to pseudo-randomly create multiple lists of close-to-equal difficulty. Normative data was subsequently collected from 62 typically-developing children and 10 adults. The data was arcsine transformed to achieve a distribution that was closer to a normal distribution, and z-scores were calculated. Even when age effects were removed, via expression of the results as z-scores, there was a highly significant correlation ($r = 0.62$, $p < 0.00001$) between performance on the dichotic free recall total and diotic conditions. This high correlation presumably reflects the large impact that cognitive skills, unrelated to dichotic perception, have on dichotic test results.

In respect to test-retest reliability, the DDdT conditions that improved significantly with practice – dichotic free recall LE, RE and total, as well as diotic, are those that would be expected to improve if cognitive skills relevant to the test got better. That is, the participant’s response "strategies" – such as visualizing the sets of numbers - are better the second time around. Test scores that we would expect to be less affected by verbal memory skills – DDdT directed left ear (LE) and right ear (RE) conditions and dichotic advantage – did not improve with practice.

Based on the percentage of the variance estimated to be accounted for by measurement error, it might at first appear from Table 5 that many of the measurements are of little value, with the error percentage varying from close to half up to 98% for 6 of the 10 measures shown. One of these measures is the free recall LE condition, which is routinely reported in auditory processing literature. Because scores for each ear are based on only 40 scored items, scores will have a significant random component that can easily be calculated from the binomial distribution. The standard deviation for repeated application of the test, even when there are no changes in true ability caused by practice, fatigue, fluctuation in attention, or variation in listening strategies is equal to $\sqrt{(P(1-P)/N)}$, where P is the true proportion of items correctly repeated and N is the number of scored items. For a test with 40 scored digits, and true scores around 80% for example (the average score for left ear free recall for an 8 year old), the expected standard deviation is 6.3%. This means that 95% of the time scores for a child with this true score will fluctuate over a range from approximately 67% to 93% (and 5% of the time the fluctuation will be even greater). Of course, practice, fatigue, fluctuations in attention and variations in listening strategy all can occur, so an even bigger fluctuation than this would be expected in practice. However, these data were obtained from typically-developing children. Were children with more aberrant scores to be included, the range of raw scores would be greater, and the percent variance accounted by measurement error would reduce accordingly.

It is evident from Figure 4 that the +2 SD limits are wider for the two REA difference measures than for either dichotic advantage or attention advantage. This is not surprising as the scores from which the REA measures are derived are each based on scores for 40 digits, whereas the dichotic and attention advantage measures are derived from scores based on 80 digits. The REA measures should thus contain greater measurement error. Consistent with this, the test-retest correlations are larger for the FR total scores and diotic scores, each of which is based on 40 digits. The very large error component of the two right ear advantage measures should be a warning against taking measurement results at face value. It is common to seize on a larger than average asymmetry in dichotic test results as an indication of an underlying problem. Quantifying the right ear advantage with z-scores as we have done makes it possible to determine whether an apparent ear asymmetry really does represent a problem, or is just the result of the child achieving better than his/her true score in one ear and poorer than his/her true score in the other, both due to chance factors.

CONCLUSION

The new dichotic digits difference test presented in this article includes a diotic condition that can act as a control to help differentiate children who perform below normal on a dichotic test due to a dichotic perception issue from those who perform below normal because of a cognitive issue. Interpretation of the control condition results is facilitated by expressing all results in age-corrected z-score units, including the differential ability to use dichotic cues when they are present. An additional study with both clinical and non-clinical participants which investigated the correlations between DDdT conditions, as well as between DDdT conditions and various cognitive abilities (memory, attention and intelligence) will be described in the companion paper (Cameron et al, in press) which follows.

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FIGURE CAPTIONS

Figure 1. DDdT graphical user interface (research version).

Figure 2. Percent of incorrect response for each digit pair combination for the 20 adults in the development study.

Figure 3. Scatterplots of the DDdT regression curves (solid line) transformed back to percentage values (i.e. percent correct): (a) FR LE; (b) FR RE; (c) FR Total; (d) DLE; (e) DRE; (f) Diotic, based on the data from the 62 children and 10 adults in the normative data study. Original data is represented by the blue circles. The dashed line represents the percentage values that correspond to the transformed values that are two standard deviations below the age-dependent mean values.

Figure 4. Scatterplots of performance on the DDdT difference measures (Dichotic Advantage, Free Recall REA, Directed REA and Attention Advantage) by the 62 children in the normative data study. The solid line indicates the mean score as a function of age, the dashed lines show the + and – 2 standard deviation limits.

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