Distortion Product Otoacoustic Emissions in Children at School Entry: A Comparison with Pure-Tone Screening and Tympanometry Results

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Abstract

This study examined the test performance of distortion product otoacoustic emissions (DPOAEs) when used as a screening tool in the school setting. A total of 1003 children (mean age 6.2 years, SD = 0.4) were tested with pure-tone screening, tympanometry, and DPOAE assessment. Optimal DPOAE test performance was determined in comparison with pure-tone screening results using clinical decision analysis. The results showed hit rates of 0.86, 0.89, and 0.90, and false alarm rates of 0.52, 0.19, and 0.22 for criterion signal-to-noise ratio (SNR) values of 4, 5, and 11 dB at 1.1, 1.9, and 3.8 kHz respectively. DPOAE test performance was compromised at 1.1 kHz. In view of the different test performance characteristics across the frequencies, the use of a fixed SNR as a pass criterion for all frequencies in DPOAE assessments is not recommended. When compared to pure tone plus tympanometry results, the DPOAEs showed deterioration in test performance, suggesting that the use of DPOAEs alone might miss children with subtle middle ear dysfunction. However, when the results of a test protocol, which incorporates both DPOAEs and tympanometry, were used in comparison with the gold standard of pure-tone screening plus tympanometry, test performance was enhanced. In view of its high performance, the use of a protocol that includes both DPOAEs and tympanometry holds promise as a useful tool in the hearing screening of schoolchildren, including difficult-to-test children.

Key Words: Distortion product otoacoustic emissions, hearing screening, schoolchildren

Abbreviations: DP-amp = distortion product amplitude; DPOAEs = distortion product otoacoustic emissions; NF = noise floor; OAEs = otoacoustic emissions; OME = otitis media with effusion; Pr[D/+] = positive predictive value; Pr[N/-] = negative predictive value; PTS = pure-tone screening; ROC = receiver operating characteristics; SNR = signal-to-noise ratios; TYM = tympanometry

Sumario

Este estudio examinó el desempeño de la prueba de emisiones otoacústicas por productos de distorsión (DPOAE) cuando se utilizó como una herramienta de tamizaje en el ambiente escolar. Se evaluó a un total de 1003 niños (edad media de 6.2 años, DS = 0.4) con audiometría de tonos puros, timpanometría

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y DPOAE. El desempeño óptimo de la prueba de DPOAE se determinó en comparación con los resultados del tamizaje con tonos puros, utilizando un análisis clínico de decisión. Los resultados mostraron tasas de acierto de 0.86, 0.89 y 0.90, y tasas de falsa alarma de 0.52, 0.19 y 0.22, para los valores del criterio de tasa de señal/ruido (SNR) de 4, 5 y 11 dB, en las frecuencias de 1.1, 1.9 y 3.8 kHz, respectivamente. El desempeño de la prueba de DPOAE se comprometió a 1.1 kHz. En vista de las diferentes características de desempeño de la prueba en las distintas frecuencias, no se recomienda el uso de una SNR fija como criterio de aprobación para todas las frecuencias en las evaluaciones con DPOAE. Cuando se compararon contra los resultados de la audiometría de tonos puros y de la timpanometría, las DPOAE mostraron deterioro en el desempeño de la prueba, sugiriendo que el uso de las DPOAE solas, puede provocar que dejemos escapar niños con disfunción sutil del oído medio. Sin embargo, cuando los resultados de un protocolo de evaluación, que incorpora tanto las DPOAE como la timpanometría, comparado contra el estándar de oro del tamizaje con tonos puros más timpanometría, los resultados de la prueba se mejoraron. En vista de este desempeño superior, el uso de un protocolo que incluya tanto las DPOAE como la timpanometría, parece constituirse como una herramienta útil en el tamizaje auditivos de niños escolares, incluyendo los niños difíciles de evaluar.

Palabras Clave: Emisiones otoacústicas por productos de distorsión, tamizaje auditivo, niños escolares

Abreviaturas: DP-amp = amplitud de los productos de distorsión; DPOAEs = emisiones otoacústicas por productos de distorsión; NF = piso de ruido; OAEs = emisiones otoacústicas; OME = otitis media con efusión; Pr[D/+] = valor

Hearing screening at school entry has been conducted in many countries for decades. The screening test usually consists of pure-tone screening audiometry and/or tympanometry. Not only does this screening procedure detect children with a sensorineural hearing loss, but it also identifies a large number of children with a conductive hearing impairment, caused predominantly by otitis media with effusion (OME) (Daly, 1991).

Hearing screening at school entry is often performed for a combination of reasons. First, it is easy for children to attend this assessment as it is held within school hours and so there is a greater rate of attendance than for earlier age screens (Robertson et al, 1995). Second, the test is inexpensive and easily administered by nurses and teachers with some basic training in hearing screening for this age group. Third, screening at school entry enables children not identified by neonatal hearing screening programs and those with fluctuating, progressive, or late-onset hearing loss to be identified (European Consensus Statement, 1998), so that educational and rehabilitational strategies may be implemented. Finally, by the time children reach this age, it is assumed that they will be able to effectively perform basic pure-tone audiometry, which provides ear and frequency specific audiometric information.

Pure-tone audiometry, however, requires a conditioned behavioral response from children. Children who are incapable of providing reliable responses to auditory stimuli are, therefore, excluded from school hearing screening programs. These include, for example, children with a short attention span, intellectual/physical impairment, learning difficulties, or children who do not understand test instructions. Decreton et al (1991) suggests that as many as 1 in 10 schoolchildren could not be adequately assessed using this traditional method. To overcome these difficulties, researchers have investigated the feasibility of using an objective measure of auditory function such as otoacoustic emissions (OAEs) for this population as an alternative hearing screening procedure (e.g., Nozza et al, 1997; Sabo et al, 2000; Driscoll et al, 2001).

Both transient evoked OAEs (TEOAEs) and distortion product OAEs (DPOAEs) have been examined as a tool for identifying hearing impairment in the school population (Nozza et al, 1997; Sabo et al, 2000; Driscoll et al, 2000, 2001, 2002; Keogh et al, 2001; O'Rourke et al, 2002). One important issue in the use of these procedures is whether performance measures (e.g., hit and false alarm rates) are adequate to justify their use as a screening instrument. Test performance, defined in this context as the ability of a test to distinguish normal hearing from hearing impaired ears, of TEOAEs for schoolchildren has recently been investigated. In a study of 940 six-year-old children using TEOAEs with a pass criterion of ≥3 dB signal-to-noise ratio (SNR), Driscoll et al (2001) found hit rates of 0.81 and 0.86, and false alarm rates of 0.05 and 0.09 at 2 and 4 kHz respectively. These results are better than that reported by Sabo et al (2000), who found a hit rate of 0.65 and a false alarm rate of 0.09 for their 583 schoolchildren aged 5 to 9 years, based on TEOAE criteria of at least 3 dB at 3 out of 4 frequencies and a whole wave reproducibility of at least 70%. The authors of both studies concluded that TEOAE screening alone would not be good enough to replace pure-tone screening for schoolchildren.

The test performance of DPOAEs may be different to that of TEOAEs, owing to differences in their intrinsic properties and recording procedures. The difference in test performance may be related to how test measurements are made and what subject group the test is targeting. Research findings obtained from adults showed that DPOAEs correctly identified normal and hearing impaired ears with good accuracy at higher frequencies (≥2 kHz) but were poor indicators of hearing impairment at the lower frequencies (Prieve et al, 1993; Gorga et al, 1993, 1999, 2000; Musiek and Baran, 1997; Dorn et al, 1999; Torre et al, 2003). For instance, Musiek and Baran (1997) obtained hit rates exceeding 0.8 and false alarm rates of about 0.2 in the high-frequency range in their study of 121 adult ears, using a combination of absolute DPOAE amplitude, SNRs (+3, +6, and +9 dB), and pure-tone cutoff values of 20, 25, and 30 dB HL as pass criteria. Dorn et al (1999) found an improvement in test performance using a multivariate statistical approach, when compared to that using the univariate clinical decision theory. The authors claimed that even if the criterion values associated with a hit rate of 0.95 and a false alarm rate of 0.05 were selected, there was considerable overlap in SNR values that made it impossible to separate normal from hearing impaired ears.

Although the test performance of DPOAEs for adults has been well documented, the corresponding information for children is not readily available. Apart from a brief report by Attias (2000), test performance measures of DPOAEs for schoolchildren are not found in the current literature. Schoolchildren are likely to have a high prevalence of middle ear dysfunction such as OME (Haggard, 1991; Kei et al, 2002). Since DPOAEs have been shown to be sensitive to the effects of OME (Topolska et al, 2000; Job and Nottet, 2002), they have the potential to be an effective screening tool for children at school entry. However, before DPOAEs can be introduced as a mass screening procedure for schoolchildren, the test performance of DPOAEs needs to be ascertained. The current study aimed to examine the test performance characteristics of DPOAEs, and in combination with tympanometry, when used as a screening tool in the school setting.

METHOD

Participants

A total of 1003 schoolchildren (528 boys and 475 girls), with a mean age of 6.2 years (range = 4.1–7.9 years, SD = 0.4), participated in the present study. Of these 1003 children, 940 participated in a previous project in which TEOAE test performance was evaluated (Driscoll et al, 2001). Written consent from children's parents and the school authority was obtained. Children with a short attention span, intellectual/physical impairment, and learning difficulties, or children who did not understand test instructions were excluded from the study.

Procedures

An audiologist who had undertaken specific training in DPOAE procedures conducted all testing. Children were tested individually, in seated position, in non-sound-treated rooms within each school. The ambient noise level of these rooms, as measured by a CEL-254 sound level meter, ranged between 34 and 51 dBA. The ambient noise was monitored during testing, and in the event of noise exceeding 50 dBA, testing was aborted and resumed when the noise subsided. An otoscopic examination was conducted by the audiologist prior to all testing to ensure that all tests were not affected by the conditions of the external ear. Pure-tone screening, tympanometry, and DPOAE testing were administered to children in a balanced order.

Pure-tone screening was performed using a Madsen Micromate 304 screening audiometer, which was fitted with ME70 noise-excluding headphones to attenuate background noise. In quiet but non-sound-treated environments in a school setting, pure tones of 20 to 25 dBHL are often used (e.g., Driscoll et al, 2001). These intensity levels represent a conservative approach to pass/fail criteria based on a compromise between true thresholds and thresholds obtainable in school testing sites. In the present study, pure-tone frequencies of 500, 1000, 2000, and 4000 Hz at an intensity level of 20 dB HL were presented. If a child failed to respond to a pure tone at any frequency at 20 dB HL for two out of three presentations, the threshold for that frequency was determined. Children with thresholds greater than 25 dB HL were considered to have failed the pure-tone screening. A cutoff value of 25 dB HL in the present study was adopted so that a fair comparison with the findings of Driscoll et al (2001) could be made.

Tympanometry with a probe tone of 226 Hz was performed using a Madsen Zodiac 901 Middle Ear Analyzer. For this age group, tympanometry is essential to detect middle ear dysfunction that reduces or obliterates OAEs (Owens et al, 1992; Nozza, 1997). Failure in tympanometry was defined as any result that could be classified as a type B or C_2 tympanogram based on a modified version of Jerger's (1970) classification system (refer to Appendix A for further detail).

DPOAEs were obtained using the GSI 60 DPOAE System. Adequacy of probe fit was inspected prior to the commencement of data acquisition. A series of simultaneous pure-tone pairs, of frequencies f_1 and f_2, at intensities of 65 and 55 dB SPL, respectively, were delivered to the test ear. All primary tones were maintained within ±1 dB of the set intensity. These stimulus intensity levels were chosen based on recommendations concerning optimal results in humans (Harris et al, 1989; Stover, 1996). The test frequency ratio (f_2/f_1) was set at 1.21 to get optimal DPOAE results (Harris et al, 1989). For each test ear, a DP-gram that plots intensity of the $2f_1$-f_2 distortion product amplitude (and mean noise floor) against f_2 frequency was obtained.

To record the DPOAEs, the default protocol, as recommended by the manufacturer, was used. Essentially, a sampling rate of 1600 was used to analyze the DPOAEs. The signal-to-noise estimates were based on a 32 Hz frequency band on either side of the emissions. A total of 300 frames (averages) were used to obtain each DPOAE. A frame would be accepted for analysis if the absolute noise level was 6 dB SPL or less and the DPOAE was at least 10 dB greater than the average noise floor. Although the use of a lower cutoff level for the noise could have reduced the noise contamination in the DPOAEs, it would significantly lengthen the test time for each child, especially when testing was performed in a non-sound-treated environment. To be accepted for analysis, the primary tones used to evoke DPOAEs were at least 40 dB greater than the noise floor. This would enable primary tones of less than or equal to 45 dB SPL to be rejected.

Data Analysis

The DPOAE SNR (defined as DPOAE amplitude minus mean noise floor for each participant) at each of the f_2 frequencies of 1.1, 1.9, and 3.8 kHz was measured and compared with the nearest audiometric frequencies (1, 2, and 4 kHz respectively). These results were plotted on a receiver operating characteristic (ROC) curve (a plot of hit rate against false alarm rate for different pass/fail criteria). ROC curves were employed in this study as they provide test performance information using a series of DPOAE SNR criteria, and thus an optimal SNR value can be determined based on some performance measures (Turner, 1991). The measures examined in the present study were hit rate (correct identification of hearing loss in a hearing impaired ear), false alarm (incorrect identification of hearing impairment in a normal-hearing ear), efficiency (number of true positive and true negative responses divided by the total number of responses), Pr[D/+] (positive predictive value: the probability of having a hearing impaired ear given a positive result), and Pr[N/-] (negative predictive value: the probability of having a normal hearing ear given a negative result) were determined using different SNR cutoff values as pass criteria at each test frequency. In determining an optimal test performance, emphasis was placed on the hit and false alarm rates, and efficiency. In practice, optimal test performance can be determined by a point on the ROC curve that is closest to the top left corner of the ROC graph. The efficiency of the test and posterior probabilities, Pr[D/+] and Pr[N/-], however, are dependent on the prevalence rates of hearing loss, which varies from population to population (Turner, 1991).

Table 1. Pure-Tone Screening and Tympanometry Results for 1003 Children

	Passed TYM	Failed TYM	Total (Ears)
Passed PTS	1725	171	1896
Failed PTS	16	94	110
Total (Ears)	1741	265	2006

Note: A failure in TYM was considered for Type B (flat) or C_2 (ear canal pressure < -200 daPa) tympanograms. A failure in PTS was indicated for pure-tone threshold exceeding 25 dB HL in at least one of the tested frequencies at 0.5, 1, 2, and 4 kHz.

RESULTS

All 1003 children were successfully tested using the above battery of tests. Table 1 presents the pure-tone screening and tympanometry data for these children (2006 ears). A total of 265 ears (13.2 %) failed tympanometry with 140 and 125 ears showing type B and C_2 tympanograms respectively. Of the 265 ears, 78 ears with type B and 93 ears with type C_2 tympanograms passed the pure-tone screening (PTS) test.

Table 2 displays the DPOAE data for children with and without a hearing loss, in combination with tympanometry outcomes (pass/fail). The mean absolute distortion product amplitude (DP-amp) for ears with normal hearing and normal tympanometric results varied slightly from 6.2 to 8.3 dB SPL across the three test frequencies (1.1, 1.9, and 3.8 kHz). In contrast, ears that failed tympanometry showed negative DP-amp values. The noise floor decreased from 2.6 to -7.0 dB SPL with increasing frequency for ears with normal hearing and normal tympanometric results. The corresponding noise floor values for other conditions followed the same trend.

While the mean DP-amp differed greatly

Table 2. DPOAE Data for 1003 Schoolchildren with and without Hearing Impairment, in Combination with Having a Pass or Fail in Tympanometry

	Normal hearing				Hearing impaired			
	Passed tympanometry N = 1725		Failed tympanometry N = 171		Passed tympanometry N = 16		Failed tympanometry N = 94	
f_2 (kHz)	DP-amp	NF	DP-amp	NF	DP-amp	NF	DP-amp	NF
1.1	6.2 (7.5)	2.6 (8.1)	-1.9 (8.1)	2.8 (8.6)	1.1 (10.7)	2.8 (9.4)	-4.7 (9.5)	4.3 (7.3)
1.9	8.3 (6.4)	-4.0 (4.6)	-0.5 (7.3)	-3.6 (6.3)	0.8 (10.9)	-2.8 (9.2)	-5.6 (7.3)	-3.0 (6.1)
3.8	8.3 (5.8)	-7.0 (2.5)	-0.6 (8.4)	-10.3 (4.9)	3.7 (6.9)	-8.5 (3.2)	-7.6 (10.6)	-12.2 (5.7)

Note: Normal hearing is defined as pure-tone threshold levels ≤25 dB HL at all tested frequencies (0.5, 1.0, 2.0, and 4 kHz). A pass in tympanometry is defined as having a Type A or C1 tympanogram. Mean values are shown (with standard deviation in parentheses) against f_2 frequency. DP-amp and NF represent distortion product amplitude (dB SPL) and noise floor (dB SPL) respectively.

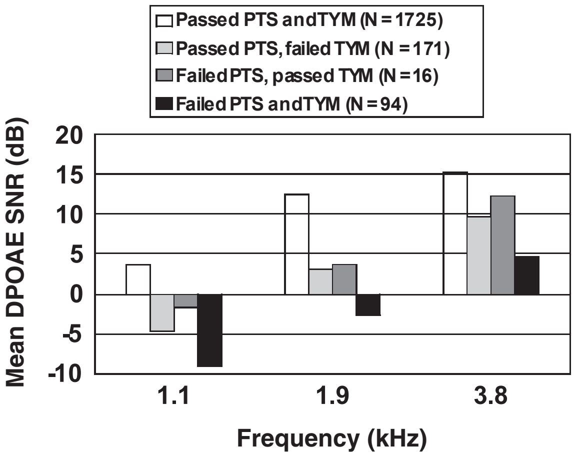

Figure 1. Mean SNR of DPOAEs as a function of PTS and TYM outcomes for 2006 ears of schoolchildren. A failure in TYM was considered for Type B (flat) or C_2 (ear canal pressure < -200 daPa) tympanograms. A failure in PTS was indicated for pure-tone threshold exceeding 25 dB HL in at least one of the tested frequencies at 0.5, 1, 2, and 4 kHz.

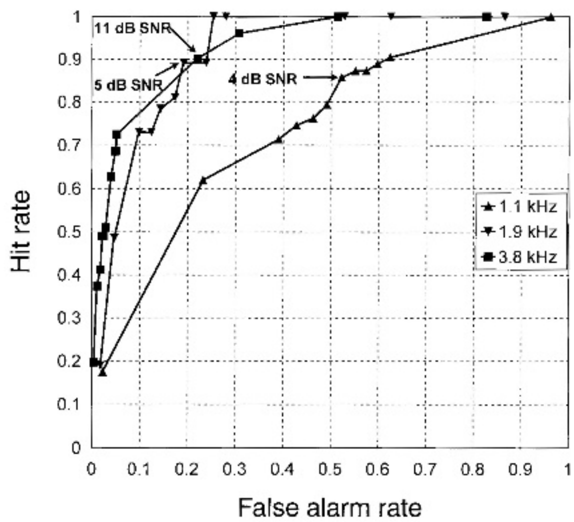

Figure 2. ROC curves for DPOAE SNR at 1.1, 1.9, and 3.8 kHz obtained with an audiometric criterion at 1, 2, and 4 kHz, respectively, for thresholds of ≤25 dB HL.

depending on the outcomes of pure-tone screening and tympanometry tests, the mean noise floors were similar across the conditions. Hence, there was a large difference in mean DPOAE SNR across the different test outcomes as shown in Figure 1. Interestingly, the mean DPOAE SNR attained a positive value (≥0 dB) at 3.8 kHz, irrespective of the test outcomes.

Figure 2 shows the ROC curves for the DPOAE test at 1.1, 1.9, and 3.8 kHz, in comparison with an audiometric criterion at 1, 2, and 4 kHz respectively for thresholds of ≤25 dB HL. Clearly, test performance measures at 1.9 and 3.8 kHz are much better than that at 1.1 kHz, in view of the higher hit and lower false alarm rates at various SNR criterion values.

Theoretically, an optimal criterion SNR value at a certain frequency can be determined primarily by examining performance measures, such as the hit, false alarm, and efficiency, across the SNR criterion values. There is usually a trade-off between the hit and false alarm rates. The ROC curve for 1.1 kHz showed optimal test performance at an SNR of 4 dB. The results for 1.9 kHz indicated optimal test performance at an SNR of 5 dB, while that for 3.8 kHz occurred at 11 dB SNR. The corresponding performance measures are shown in Table 3. The performance measures at other SNR criterion values for these frequencies are shown in Appendix B.

Figure 3 depicts the ROC curves for DPOAE SNR at 1.1, 1.9, and 3.8 kHz obtained with an audiometric criterion at 1, 2, and 4 kHz respectively for thresholds of ≤25 dB HL and normal tympanometric findings. These ROC curves revealed deterioration in test performance, when compared to those curves in Figure 2. Again, the test performance measures at 1.1 kHz were compromised.

Owing to the generally poor performance at 1.1 kHz, optimal performance measures can hardly be determined. For a criterion SNR of 0 to 4 dB, the hit rate lies between

Table 3. Test Performance Measures for DPOAEs in Comparison with Pure-Tone Screening Results at a Specific Criterion SNR

Frequency	SNR	Hit rate	False alarm rate	Efficiency	Pr[D/+]	Pr[N/-]
1.1 kHz	4 dB	0.86	0.52	0.55	0.27	0.94
1.9 kHz	5 dB	0.89	0.19	0.82	0.52	0.97
3.8 kHz	11 dB	0.90	0.22	0.80	0.48	0.97

Table 4. Test Performance Measures for DPOAEs at a Specific Criterion SNR in Comparison with Pure-Tone Screening and Tympanometry Results

Frequency	SNR	Hit rate	False alarm rate	Efficiency	Pr[D/+]	Pr[N/-]
1.9 kHz	5 dB	0.62	0.14	0.82	0.50	0.91
3.8 kHz	11 dB	0.68	0.17	0.80	0.48	0.92

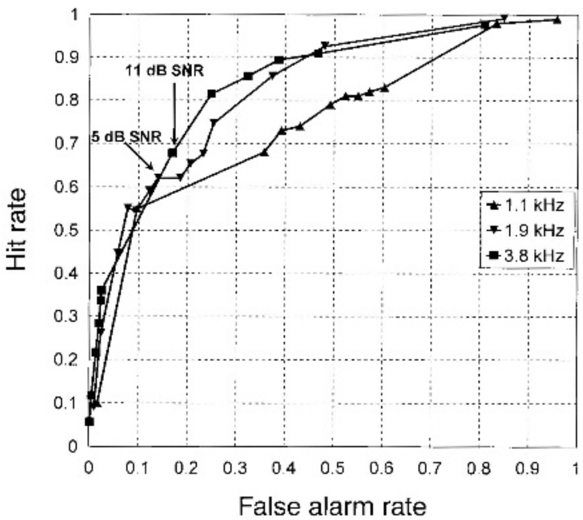

Figure 3. ROC curves for DPOAE SNR at 1.1, 1.9, and 3.8 kHz obtained with an audiometric criterion at 1, 2, and 4 kHz, respectively, for thresholds of ≤25 dB HL and normal tympanometric results.

0.68 and 0.79 against a corresponding false alarm rate of between 0.36 and 0.49. While the negative predictive values are high (≥0.9), the corresponding positive predictive values are low (≤0.3). Overall, the efficiency is moderate with values ranging from 0.56 to 0.65 (see Appendix C for details). Table 4 shows the optimal test performance measures at both 1.9 and 3.8 kHz. As shown, the performance measures corresponding to these two frequencies are comparable. When compared to Table 3, the performance measures showed a substantial drop in hit rates.

The use of OAEs combined with tympanometry may be used to identify hearing dysfunction in difficult-to-test children (e.g., Driscoll et al, 2002). For this reason, the efficacy of this protocol needs to be determined when compared with the traditional protocol of pure-tone screening combined with tympanometry. The following analysis evaluates the test performance of four protocols against the gold standard of pure-tone screening plus tympanometry: Protocol 1—a pass was awarded if DPOAE SNR ≥5 dB at 1.9 kHz plus normal tympanometry results; Protocol 2—a pass was awarded if DPOAE SNR ≥11 dB at 3.8 kHz plus normal tympanometry results; Protocol 3—a pass was awarded if DPOAE SNR ≥5 dB at 1.9 kHz and SNR ≥11 dB at 3.8 kHz plus normal tympanometry results; Protocol 4—a pass was awarded if DPOAE SNR ≥5 dB at 1.9 kHz or SNR ≥11 dB at 3.8 kHz plus normal tympanometry results. Tables 5, 6, 7, and 8 containing decision matrices for the four protocols are derived from raw data. The performance indicators of these protocols are shown in Table 9. As shown in Table 9, the hit rates for the four protocols are ≥0.96. While the hit rate of Protocol 3 is slightly better than the other three protocols, its false alarm rate is the worst among the protocols. In contrast, although the hit rate of Protocol 4 is slightly worse than the other three protocols, its false alarm rate, efficiency, and positive predictive value are the best among the protocols.

Table 5. Decision Matrix for Protocol 1, in Comparison with the Gold Standard of Pure-Tone Screening Plus Tympanometry Results

Gold standard	Failed protocol	Passed protocol	Total (Ears)
Abnormal	273	8	281
Normal	241	1484	1725
Total (Ears)	514	1492	2006

Note: Protocol 1: A pass was awarded if DPOAE SNR ≥5 dB at 1.9 kHz plus normal tympanometry results.

Table 6. Decision Matrix for Protocol 2, in Comparison with the Gold Standard of Pure-Tone Screening Plus Tympanometry Results

Gold standard	Failed protocol	Passed protocol	Total (Ears)
Abnormal	273	8	281
Normal	289	1436	1725
Total (Ears)	562	1444	2006

Note: Protocol 2: A pass was awarded if DPOAE SNR ≥11 dB at 3.8 kHz plus normal tympanometry results.

Table 7. Decision Matrix for Protocol 3, in Comparison with the Gold Standard of Pure-Tone Screening Plus Tympanometry Results

Gold standard	Failed protocol	Passed protocol	Total (Ears)
Abnormal	277	4	281
Normal	440	1285	1725
Total (Ears)	717	1289	2006

Note: Protocol 3: A pass was awarded if DPOAE SNR ≥5 dB at 1.9 kHz and SNR ≥11 dB at 3.8 kHz plus normal tympanometry results.

Table 8. Decision Matrix for Protocol 4, in Comparison with the Gold Standard of Pure-Tone Screening Plus Tympanometry Results

Gold standard	Failed protocol	Passed protocol	Total (Ears)
Abnormal	269	12	281
Normal	92	1633	1725
Total (Ears)	361	1645	2006

Note: Protocol 4: A pass was awarded if DPOAE SNR ≥5 dB at 1.9 kHz or SNR ≥11 dB at 3.8 kHz plus normal tympanometry results.

DISCUSSION

The use of pure-tone screening audiometry plus tympanometry has been a standard screening procedure for identifying hearing impairment in schoolchildren for years. As documented in the literature, there is a high prevalence of middle ear dysfunction in this population. For this reason, tympanometry needs to be included in the battery of tests if the purpose of the screening is to identify middle ear problems as well as hearing impairment in this population. The results of the present study showed that 265 of 2006 (13.2 %) ears failed tympanometry. Of these ears, a significant number actually passed the pure-tone screening test (see Table 1), indicating that ears with middle ear dysfunction could pass the pure-tone screening test when a rather lenient cutoff value of 25 dB HL was used. If a cutoff of 15 dB HL were used instead, the proportion of ears with middle ear dysfunction that passed pure-tone screening could be minimized. However, using 15 dB HL as a cutoff criterion in hearing screening at schools is not logistically feasible, given that testing is predominantly performed in non-sound-treated rooms.

In the current study, the criteria for a pass in tympanometry were primarily based on Jerger's (1970) classification. A more stringent set of criteria for assessing the middle ear function of children could have identified ears with subtle middle ear dysfunction that are not identified using the current classification system. For instance, Silman et al (1992) have demonstrated higher sensitivity and specificity when a failure occurs in any one of the following measures: tympanometric width (>150 daPa = fail), static admittance (≤0.1 = fail), ipsilateral acoustic reflex at 1000 Hz (no response at 110 dB HL = fail), and tympanometric peak pressure (≤-100 daPa = fail). Silman et al (1992) found these criteria especially useful for identifying those with OME but no hearing loss in the 1–4 kHz region.

As discussed above, pure-tone screening test and tympanometry evaluate different aspects of auditory function. The DPOAE test, on the other hand, measures the emissions from the outer hair cells inside the cochlea. The successful recording of DPOAEs depends, among other factors, on the integrity of the outer hair cells and normal middle ear function. Hence the outcomes (pass/fail) of pure-tone screening,

Table 9. Performance Indicators for Four Test Protocols, in Comparison with the Gold Standard of Pure-Tone Screening Plus Tympanometry Results

Protocol	Hit rate	False alarm rate	Efficiency	Pr[D/+]	Pr[N/-]
1	0.97	0.14	0.88	0.53	0.99
2	0.97	0.16	0.85	0.49	0.99
3	0.99	0.26	0.78	0.39	> 0.99
4	0.96	0.05	0.95	0.75	0.99

Note: Protocol 1: A pass was awarded if DPOAE SNR ≥5 dB at 1.9 kHz plus normal tympanometry results. Protocol 2: A pass was awarded if DPOAE SNR ≥11 dB at 3.8 kHz plus normal tympanometry results. Protocol 3: A pass was awarded if DPOAE SNR ≥5 dB at 1.9 kHz and SNR ≥11 dB at 3.8 kHz plus normal tympanometry results. Protocol 4: A pass was awarded if DPOAE SNR ≥5 dB at 1.9 kHz or SNR ≥11 dB at 3.8 kHz plus normal tympanometry results.

tympanometry, and DPOAEs are not necessarily the same, even for the same group of schoolchildren. The research question is: how similar (or different) are the outcomes of the three tests? The present study aimed at evaluating the use of DPOAEs as a screening tool for the identification of hearing impairment and middle ear dysfunction in children at school entry. The mean DP-amp obtained from normal-hearing children (with a pass in both PTS and tympanometry) ranged from 6.2 to 8.3 dB SPL. These findings compare favorably with the results of Musiek and Baran (1997) for normal adult ears (6.0–7.1 dB SPL). The mean noise floor, however, was much higher than that reported in the Musiek and Baran study, which was conducted in sound-treated chambers. For this reason, the SNR obtained from the present study was greatly reduced in comparison to their study.

The mean DP-amp in ears that failed pure-tone screening or tympanometry or both dropped by 4.6 to 15.9 dB, when compared to normal ears (see Table 2). The decrease in DP-amp for those ears that passed PTS but failed tympanometry ranged from 8.1 to 8.9 dB. These findings are expected given that middle ear dysfunction reduces or obliterates OAEs (Glattke and Kujawa, 1991; Owens et al, 1992).

The ROC analysis of the current study indicated that the test performance of DPOAEs was better at high frequencies than at the low frequencies, in keeping with the findings of Gorga et al (1993), Prieve et al (1993), Musiek and Baran (1997), and Attias (2000). As suggested, a high level of background noise centered at the low frequencies was the main reason for this phenomenon to occur. Hence, the interpretation of DPOAE findings at 1.1 kHz for school screening should be made with caution, given the low hit and high false alarm rates (see Table 3). Torre et al (2003) also reported that there was considerable overlap between DPOAE responses and noise levels at 1 kHz, resulting in poor test performance at this frequency. The test performance indicators at 1.9 and 3.8 kHz from the present study (shown in Table 3), though not ideal, are much better than that at 1.1 kHz, in keeping with the results reported by Gorga et al (1997) and Torre et al (2003). In particular, these performance indicators are comparable to that obtained by Driscoll et al (2001) for the TEOAEs. They obtained a hit rate of 0.81 and 0.86, and a false alarm rate of 0.05 and 0.09 at 2 and 4 kHz respectively, from practically the same cohort of schoolchildren as for the current study.

There is always a trade-off between the hit and false alarm rates, when determining an optimal value for the test performance using clinical decision analysis. A high hit rate is usually accompanied by a high false alarm rate. Hence, depending on the purpose of the test, a balance between these rates has to be made. If the DPOAE test is to identify schoolchildren for hearing impairment in excess of 25 dB HL, the best option is to minimize false alarm rates while keeping a reasonably adequate hit rate (e.g., >0.8). This would help to reduce parental anxiety and minimize resources required for running the hearing screening program.

Many clinicians have attempted to employ a fixed criterion SNR (e.g., 6 dB) for all test frequencies in DPOAE assessments. However, the results of the current study indicated that this might not give optimal test performance because the optimal criterion for SNR varied across the frequencies. In particular, the mean DPOAE SNR at 3.8 kHz registered a positive value even for ears that failed both pure-tone screening and tympanometry (see Figure 1). In view of the robust DPOAEs at this frequency, the criterion SNR has to be raised to give optimal results (see Tables 3 and 4). The above findings are also supported by the findings of Gorga et al (1999), who examined DPOAE performance using SNR criteria of 3, 6, and 9 dB in comparison to pure-tone audiometric findings. The hit rate was less than 90% for all test frequencies, even when the most stringent SNR of 9 dB was used.

When DPOAE performance was evaluated against a gold standard using both pure-tone screening and tympanometric results, the performance indicators deteriorated with lower hit rates (0.62–0.68) (see Table 4), in comparison to that evaluated against pure-tone screening results alone. This finding implies that the use of the DPOAE test alone in hearing screening would have missed about 32 to 38% of children who failed the protocol of pure-tone screening plus tympanometry. Like pure-tone audiometry with a cutoff of 25 dB HL for normal hearing, the DPOAE test is not highly sensitive to middle ear dysfunction in this cohort of children. Although middle ear dysfunction usually affects hearing acuity more in the low than at the higher frequencies, DPOAE performance did not seem to improve as the test frequency was decreased (see Figure 3). Noise contamination was the main hurdle for obtaining good test performance at the lower frequencies.

Given the high prevalence of middle ear dysfunction in schoolchildren, a complete test protocol involving both DPOAEs and tympanometry is essential. In the current study, four such protocols were compared against the gold standard of pure-tone screening plus tympanometry. The results (shown in Table 9) showed a marked improvement in test performance when compared to that based on DPOAE results alone (compare with Tables 3 and 4). Given these results, the use of a combination of DPOAEs and tympanometry in identifying auditory dysfunction in the general school population is superior to that using the DPOAE test alone. The higher performance of the protocols could be due to the inclusion of tympanometric measures, which are more sensitive to either the PTS or DPOAEs in identifying middle ear dysfunction that is prevalent in this population. Hence the inclusion of tympanometric results in both PTS and DPOAEs in the above analyses is a dominating factor that improved the overall test performance.

The high test performance of the four protocols suggests that these protocols can play an important role in hearing screening programs for schoolchildren. Since DPOAEs and tympanometry are objective measures of auditory function, the use of a protocol that includes both measures holds promise as an indispensable tool for testing children who do not understand test instructions. The earlier work of Driscoll et al (2002), who successfully tested difficult-to-test children studying in special schools using TEOAEs and tympanometry, provide evidence to this effect. However, despite all these advantages, clinicians should be aware of the limitations of DPOAE testing such as the effect of excessive physiologic and ambient noise on test results for children in the target population with heavy breathing or cleft palate. Also, children with a low frequency (≤1 kHz) sensorineural hearing loss or auditory neuropathy may not be identified using these objective measures (Doyle et al, 1998).

In summary, the DPOAE data from the present study showed good hit rates and false alarm rates for 1.9 and 3.8 kHz, but test performance was compromised for the lowest frequency (1.1 kHz). When compared to pure-tone plus tympanometry results, the test performance measures of DPOAEs deteriorated across all frequencies. The present study does not support the use of a fixed SNR for all test frequencies in DPOAE assessments because the optimal SNR criterion varies across the frequencies. Most importantly, the findings of the present study lend support to the use of a protocol, which incorporates DPOAEs and tympanometry, for screening schoolchildren.

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Appendix A. Classification of Tympanograms

Tympanogram type	Middle ear pressure (daPa)	Static compliance (ml)
Type A	+50 to -100	0.2–1.5
Type B	no peak	–
Type C1	-101 to -200	0.2–1.5
Type C2	< -200	0.2–1.5

Appendix B. Test Performance Measures of DPOAEs in Comparison with Pure-Tone Screening Results

Frequency	SNR (dB)	Hit rate	False alarm rate	Efficiency index	Pr[D/+]	Pr[N/-]
1.1 kHz	-20	0.18	0.02	0.83	0.63	0.84
	-5	0.62	0.23	0.74	0.38	0.90
	0	0.71	0.39	0.63	0.29	0.90
	1	0.75	0.43	0.61	0.29	0.91
	2	0.76	0.46	0.58	0.27	0.91
	3	0.79	0.49	0.56	0.27	0.92
	4	0.86	0.52	0.55	0.27	0.94
	5	0.87	0.55	0.53	0.27	0.94
	6	0.87	0.57	0.51	0.26	0.94
	7	0.89	0.60	0.49	0.25	0.94
	8	0.91	0.62	0.47	0.25	0.95
	20	1.00	0.96	0.22	0.19	1.00
1.9 kHz	-10	0.19	0.02	0.83	0.71	0.84
	-5	0.49	0.05	0.87	0.70	0.89
	0	0.73	0.10	0.87	0.63	0.94
	2	0.73	0.12	0.85	0.57	0.93
	3	0.78	0.14	0.84	0.56	0.95
	4	0.81	0.17	0.82	0.52	0.95
	5	0.89	0.19	0.82	0.52	0.97
	7	0.89	0.24	0.79	0.46	0.97
	8	1.00	0.25	0.79	0.47	1.00
	9	1.00	0.28	0.77	0.45	1.00
	13	1.00	0.53	0.57	0.30	1.00
	15	1.00	0.62	0.49	0.27	1.00
	20	1.00	0.86	0.30	0.21	1.00
3.8 kHz	-5	0.20	0.00	0.85	0.92	0.84
	0	0.37	0.01	0.87	0.89	0.87
	2	0.41	0.02	0.88	0.84	0.88
	3	0.49	0.02	0.89	0.84	0.89
	4	0.49	0.02	0.89	0.82	0.89
	5	0.51	0.03	0.89	0.80	0.90
	7	0.63	0.04	0.90	0.78	0.92
	9	0.69	0.05	0.90	0.76	0.93
	10	0.73	0.05	0.91	0.76	0.94
	11	0.90	0.22	0.80	0.48	0.97
	12	0.96	0.31	0.74	0.42	0.99
	15	1.00	0.51	0.58	0.31	1.00
	20	1.00	0.83	0.33	0.22	1.00

Appendix C. Test Performance Results for DPOAEs in Comparison with Pure-Tone Screening Plus Tympanometry

Frequency	SNR (dB)	Hit rate	False alarm rate	Efficiency index	Pr[D/+]	Pr[N/-]
1.1 kHz	-20	0.10	0.02	0.82	0.57	0.83
	-5	0.55	0.10	0.84	0.56	0.90
	0	0.68	0.36	0.65	0.30	0.90
	1	0.73	0.39	0.63	0.30	0.91
	2	0.74	0.43	0.60	0.28	0.91
	4	0.79	0.49	0.56	0.27	0.92
	5	0.81	0.52	0.54	0.26	0.91
	6	0.81	0.55	0.52	0.25	0.91
	7	0.82	0.57	0.50	0.25	0.91
	8	0.83	0.60	0.48	0.24	0.91
	15	0.98	0.83	0.32	0.21	0.97
	20	0.99	0.96	0.22	0.19	0.96
1.9 kHz	-10	0.09	0.01	0.82	0.68	0.83
	-5	0.26	0.02	0.84	0.71	0.85
	0	0.45	0.06	0.85	0.64	0.88
	2	0.55	0.08	0.85	0.62	0.90
	3	0.55	0.09	0.84	0.57	0.90
	4	0.59	0.12	0.82	0.53	0.90
	5	0.62	0.14	0.82	0.50	0.91
	7	0.62	0.18	0.78	0.43	0.90
	8	0.65	0.21	0.77	0.42	0.91
	9	0.68	0.23	0.75	0.40	0.91
	10	0.75	0.25	0.75	0.40	0.93
	11	0.86	0.37	0.67	0.34	0.95
	13	0.93	0.48	0.60	0.31	0.97
	20	0.99	0.85	0.31	0.21	0.99
3.8 kHz	-5	0.06	0.00	0.82	0.93	0.82
	0	0.12	0.00	0.83	0.84	0.83
	5	0.22	0.01	0.84	0.78	0.85
	7	0.28	0.02	0.85	0.76	0.86
	9	0.34	0.02	0.86	0.76	0.86
	10	0.36	0.02	0.86	0.77	0.87
	11	0.68	0.17	0.80	0.48	0.92
	12	0.81	0.25	0.76	0.43	0.95
	13	0.86	0.32	0.71	0.38	0.95
	14	0.89	0.39	0.67	0.35	0.96
	15	0.91	0.47	0.60	0.31	0.96
	20	0.98	0.81	0.34	0.22	0.97