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Original Article

Comparison of two tests of auditory temporal resolution in children with central auditory processing disorder, adults with psychosis, and adult professional musicians

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Abstract

Objective: Evaluate auditory temporal resolution threshold outcomes across three different populations. *Design:* Two commercially available tests of auditory gap detection (Random gap detection (RGDT) test, and Gaps-in-noise (GIN) test) were administered to all participants. *Study sample:* Adult professional musicians (APM) (N = 11, age range 28–61 years); children with central auditory processing disorder (CAPD) (N = 22, age range 7.5–17 years); and first episode psychosis patients (FEP) (N = 17, age range 18–48 years). *Results:* It was not possible to calculate a threshold for the RGDT for 13 of 22 children with CAPD and for 7 of 17 adults with FEP due to response inconsistency. Analysis of variance (ANOVA) excluding cases that produced inconsistent RGDT results showed that only RGDT thresholds differed across groups (F = 8.73, p = 0.001). Three t-tests comparing test means within group revealed statistically significant differences between the gap detection thresholds obtained with the RGDT vs. the GIN for each group. No significant correlations were seen between RGDT and GIN. *Conclusion:* Lower/better gap detection thresholds and smaller standard deviations were obtained using the GIN in all three groups. Lack of correlation between the two tests suggests that they may measure different processes.

Key Words: Temporal resolution; auditory gap detection; central auditory processing disorder; schizophrenia; auditory processing; musicians; children

Auditory perception extends beyond hearing sensitivity, as measured by the pure-tone audiogram, including processing of auditory elements essential to speech segregation. Auditory processing is linked to language and speech skills. Temporal processing is a component of auditory processing describing processing of time-related changes of auditory information. Specific auditory skills of temporal processing are temporal integration, temporal sequencing, temporal masking, and temporal resolution (ASHA, 1996). These processes may affect phoneme discrimination, speech in noise perception, duration discrimination, rhythm perception, and prosodic distinction (Phillips, 2002; Chermak & Musiek, 1997). Temporal resolution, defined as the shortest time period over which the ear can discriminate two signals (Gelfand, 2004) may be linked to language acquisition and cognition (Fingelkurts & Fingelkurts, 2006; Bao et al, 2013; Grube et al, 2012, 2013), although this purported linkage is complex (see for example Studdert-Kennedy & Mody, 1995; Bishop et al, 1999; Nittrouer, 1999; Specht, 2014).

Temporal resolution testing is essential in the clinical setting when addressing auditory perception in general, and specifically auditory processing, because it provides information on an individual's ability to differentiate rapidly changing sounds (e.g. stop consonants). In children, temporal resolution contributes to normal language acquisition, since being able to perceive and respond to speech sound changes is a core element of language learning. Receptive language skills and speech production seem to be influenced by temporal resolution (Rance et al, 2004). Rapid temporal processing and precise timing of auditory events may contribute to the development of basic pre-reading and reading skills during childhood (Walker et al, 2002; Hautus et al, 2003; Griffiths & Warren, 2002). Temporal resolution improves as children mature (Shinn et al, 2009). The exact time line of maturation is not clear and discrepancies across published studies may be the result of different testing approaches, some of which may not be optimally designed for the clinical setting. Temporal resolution is impaired in older adults, as reported in 9 of 12 studies

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Abbreviations

APM	Adult professional musicians
CAPD	Central auditory processing disorder
FEP	First episode psychosis
GIN	Gaps in noise test
RGDT	Random gap detection test

of normal hearing older adults and in 12 of 13 studies of older adults with hearing loss (Humes et al, 2012). In these studies, age but not hearing loss, was determined to be a contributing factor to changes in temporal resolution.

Gap detection testing, as a measure of temporal resolution, is considered a straightforward approach (Boets et al, 2006) and offers insights into auditory perception (Phillips, 1999) that may relate to speech perception (Phillips & Smith, 2004). Clinical assessment of gap detection has increased in recent years as clinically feasible procedures have become available and the role of tests using non-verbal stimuli in the assessment of central auditory function and the diagnosis of central auditory processing disorder has drawn greater attention (AAA, 2010; BSA, 2011).

Commercially available tests include the Gaps-in-noise (GIN) test (Musiek et al, 2005) and the Random gap detection (RGDT) test (Keith, 2000). Although the names of these two tests suggest they measure the same auditory process, they differ in a number of ways, including presentation mode (i.e. monaural vs. binaural), stimuli (i.e. noise vs. tones), response mode (i.e. motoric vs. verbal), response task (i.e. motor vs. counting), total number of trials (i.e. 60 noise gaps vs. 45 tones), and the approach to measuring the shortest gap detected (i.e. shortest interval in which a gap is detected on 4 of 6 presentations vs. the shortest gap the listener perceives as two tones). As noted by Chermak and Lee (2005), the GIN is a true measure of auditory gap detection as it measures the smallest silent interval detectable by a listener, while the RGDT appears to confound gap detection and fusion as the listener's task is to indicate whether one or two distinct tones are heard, the former indicating the perception of a fused image or silent interval in a stimulus that a listener *does not detect*.

The neurophysiology underlying these two tasks may differ significantly (Eggermont, 1995; Mickey & Middlebrooks, 2001; Phillips, 1999; Phillips et al, 2010), leading to possible discrepancies in the clinical findings regarding detection and fusion abilities. (Kazui et al, 1990). Moreover, a strong age or maturation effect is seen for the RGDT (Iliadou et al, 2009), while normative values for the GIN are age independent (Shinn et al, 2009). This may be attributed, at least in part, to the different response modes of the two tests (i.e. motoric vs. verbal counting) and/or the limitations in determining a gap detection threshold on the basis of only one (RGDT) versus six trials (GIN) for each specific gap duration. The sensitivity of the GIN to central auditory nervous system (CANS) involvement has been documented, with elevated (worse) thresholds in adults with confirmed neurological involvement of the CANS (Musiek et al, 2005). To the authors' knowledge, sensitivity of the RGDT has not been established.

The present study examined the performance of three different populations (adult professional musicians, children diagnosed with central auditory processing disorders [CAPD], and patients presenting with their first episode psychosis) on two tests of temporal resolution. Our objective was to identify differences across groups as well as across tests. Comparing the performance of children with CAPD across temporal resolution measures can provide information to indicate if both tests may be equally sensitive to CAPD in this population. In addition to differences across tests due to the differences noted above, we also anticipated differences across groups, as elaborated next.

Adult professional musicians were expected to present an optimum response, given reports of their superior auditory processing abilities (Zendel & Alain, 2012; Kraus & Anderson, 2013). Musicians have been shown to have better frequency discrimination abilities than non-musicians (Kishon-Rabin et al, 2001; Micheyl et al, 2006). Auditory temporal-interval discrimination thresholds are lower/better in musicians and their advantage, as it exists in both fixed and variable conditions, seems to be attributed to better temporal processing as opposed to better predictive mechanisms (Banai et al, 2012). Of interest, Banai and Ahissar (2013) found that eight-year-old children with musical education had better auditory temporal-interval discrimination as well as frequency discrimination, which was correlated with reading skills.

Adult patients presenting with their first episode psychosis, which may be a precursor to schizophrenia, were included in the present study because central auditory processing deficits, including temporal resolution deficits, have been reported in patients with schizophrenia (Iliadou et al, 2013). These processing deficits might underlie auditory hallucinations (McLachlin et al, 2013). Specifically, a fundamental temporal coordination deficit is thought to be present in schizophrenia leading to timing dysfunctions of perceptual, cognitive, and motor processes (Tononi & Edelman, 2000). This deficit is evident with greater timing variability under both millisecond and several-second timing conditions in patients with schizophrenia as opposed to a control group. (Carroll et al, 2009).

Material and Methods

Two different tests of temporal resolution were administered to three different groups: adult professional musicians (APM) (N = 11, age range 28–61 years); children with CAPD (N = 22, age range 7.5–17 years); and first episode psychosis patients (FEP) (N = 17, age range 18–48 years). All subjects had normal pure-tone thresholds better than 20 dB HL for all octave frequencies between 250 and 8000 Hz, bilaterally.

CAPD was diagnosed on the basis of abnormal results (more than two standard deviations from the normative values) in at least one ear on at least two of the four tests used, as per the American Speech-Language-Hearing Association (ASHA, 2005) and American Academy of Audiology (2010) proposed diagnostic criteria. In addition, at least one test with observed deficits had to be non-speech according to the British Society of Audiology's (2011) proposed definition for APD. The two verbal tests were the monaural low-redundancy Greek speech in babble test (Iliadou et al, 2006, 2009) and the Greek dichotic digits test (Iliadou et al, 2010). The two nonverbal tests were by Auditec St. Louis and included the monaurally conducted temporal sequencing Frequency Pattern Test and Duration Pattern Test.

The Random gap detection (RGDT) test (Keith, 2000) and the Gaps-in-noise (GIN) test (Musiek et al, 2006; Shinn et al, 2009) were administered to all participants in that order. Both tests purportedly examine temporal resolution; however, as outlined above, the GIN may provide a truer measure of gap detection and the RGDT might reflect, at least in part, auditory fusion. Also, as outlined above, the GIN and the RGDT differ in a number of ways, including presentation mode (i.e. monaural vs. binaural), type of stimuli presented (i.e. noise vs. tones), response mode (i.e. motoric vs. verbal), response task (i.e. motor vs. counting), total number of gap presentations (i.e. 60 noise gaps vs. 45 tones), and the approach to measuring the shortest gap detected (i.e. shortest interval in which a gap is detected on 4 of 6 presentations vs. shortest gap that results in the perception of two tones in one presentation), respectively.

Both tests were administered in a sound-treated booth using recorded material that was played on a CD-player through an audiometer at 60 dB HL.

The RGDT was presented binaurally following successful completion of a practice section. The practice as well as the main section consists of pairs of pure tones separated by silent intervals: silent intervals for the practice section start at 0 msec and gradually increase to 40 msec. In the main section of the test, the silent intervals are presented in random order for each of the following pure tones: 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz, which are tested in sequence. A 4.5 second inter-trial interval is used to allow subjects time to respond. Nine trials are presented in the practice section and nine for each of the frequencies tested. Each trial for each pure-tone frequency is presented once with a unique silent interval (i.e. gap). A total of 36 trials are used to calculate the overall gap detection threshold. The participant's task is to report whether one or two sounds was heard. The threshold of gap detection is calculated for each frequency tested as the shortest time interval at which the participant reports perception of two tones. Averaging the gap detection threshold of each of the four frequencies tested provides the average gap detection threshold across frequencies.

The GIN was presented monaurally, starting with the practice section for each ear. The practice test consists of 10 trials with random presentation of varying durations of gaps in white noise. The GIN is comprised of four lists with 32 to 36 trials each: list 1 has 35 trials, list 2 has 32, list 3 has 29, and list 4 contains 36 trials. Each trial consists of 6 seconds of white noise with a 5 second inter-trial-interval. Duration and location of the gaps is varied. The duration of the gaps is 2, 3, 4, 5, 6, 8, 10, 12, 15, and 20 msec. Each gap duration occurs six times within each list. Each subject was told that they were going to hear noise in which there might be short gaps with no noise, that some gaps would be shorter than others, and that in some cases no gaps would be present. The participant was told to indicate when they detected a gap by pressing a button. After each ear had been tested, the number and percent of correct responses for each gap duration was calculated. Gap detection threshold was calculated as the shortest gap duration detected on at least four out of six gaps. False positives were noted and subtracted from the correct responses as follows: total score = (total number of correct responses-false positives)/the number of trials in the list (29–36).

Results

It was not possible to calculate a threshold for the RGDT for 13 of 22 children with CAPD and for 7 of 17 adults with FEP due to response inconsistency. Response inconsistency was noted when, despite completing the practice items with consistency (i.e. a clear-cut threshold), during the main section of the test the subjects were reporting "2" for a 0 msec gap between tones while reporting "1" for 40 msec gaps between tones, or were reporting "1" and "2" tone responses in an arbitrary fashion (e.g. reporting hearing '2' for shorter gaps and interchanging "1" and "2" responses for longer gaps). Data (mean and standard deviations) of both temporal resolution tests for all three groups are plotted for comparison in Figure 1. Standard deviation is a measure of variance or data distribution (Kirkwood & Sterne, 2003).

A one-way analysis of variance (ANOVA) comparing means of RGDT and GIN across the three groups revealed that RGDT thresholds ($F = 19.46$, $p = 0.0001$) and GIN left ear thresholds (GINthresLE) ($F = 30.45$, $p = 0.043$) were statistically significantly different across the three groups.GIN right ear thresholds (GINthresRE) did not differ from the GINthresLE or the RGDT thresholds ($F = 27.43$, $p = 0.063$). An additional ANOVA, excluding cases that produced inconsistent RGDT thresholds, showed that only RGDT thresholds were significantly different across groups ($F = 8.73$, $p = 0.001$); with GINthresRE ($F = 0.24$, $p = 0.78$) and GINthresLE ($F = 1.6$, $p = 0.22$) showing non-significant differences across groups. Three t-tests comparing the means within each group (nine t-tests total) revealed statistically significant differences between the gap detection thresholds obtained with the RGDT vs. the GINthresRE, RGDT vs. the GINthresLE, and GINthresRE vs. GINthresLE for each group. Excluding inconsistent cases produced the same results (Table 1).

Six of 22 children with CAPD failed the RGDT. Another 13 of the 22 children with CAPD performed inconsistently and were assigned an RGDT threshold exceeding 40 msec and therefore were included in the group of children who failed the test. In total 19 of 22 children were considered to have failed the RGDT (defined as performance > 20 msec for children up to 9 years 11 months; > 11.8 msec for children between 10 years and 10 years 11 months; > 10 msec for children between 11 years and 11 years 11 months; and > 8.75 msec for children older than 12 years-of-age). Only 6 of 22 children with CAPD failed the GIN (defined as > 8 msec). Seven of 17 FEP patients presented inconsistent RGDT thresholds and were assigned thresholds of 40 msec. All FEP participants failed the RGDT, by exhibiting thresholds of more than 8 msec. The professional musician group was the only group in which no member presented RGDT thresholds exceeding 40 msec. All musicians passed both the RGDT and the GIN right and left ears (See Table 2).

No significant correlations between RGDT and GIN scores were seen within groups; however, significant (but weak) correlations

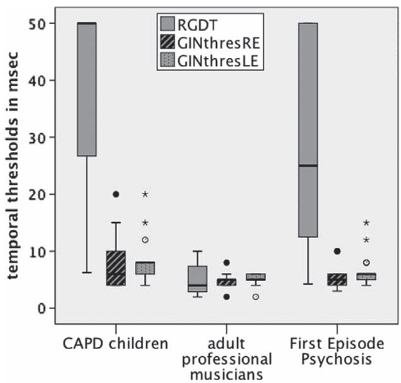

Figure 1. Data (mean and standard deviations) of both temporal resolution tests for all three groups are plotted for comparison.

Table 1. Consistency and distribution differences Mean differences in msec of the two temporal resolution tests (RGDT & GIN) within each group tested in total cases of each group; in cases showing inconsistent results in some cases, in cases showing consistency. All values shown are in msec with values outside parentheses showing mean threshold values in each group & condition (consistent or not, and total); values inside parentheses are standard deviations showing distribution of data.

	RGDT	*GIN RE*	*GIN LE*
CAPD total	32 (± 12)	7.3 (± 4)	7.8 (± 3.6)
CAPD inconsistent cases	> 40	8.5 (± 4.4)	9 (± 4)
CAPD consistent cases only	18.09 (± 9.1)	5.2 (± 2)	5.8 (± 1.4)
APM total	5 (± 2.9)	4.8 (± 1.4)	5 (± 1.1)
APM inconsistent cases	N/A	N/A	N/A
APM consistent cases only	5 (± 2.9)	4.8 (± 1.4)	5 (± 1.1)
FEP total	24.7 (± 14.5)	5.7 (± 2.2)	6.6 (± 2.8)
FEP inconsistent cases	> 40	7 (± 2.8)	7.7 (± 4.1)
FEP consistent cases only	14.1 (± 8.4)	4.8 (± 1)	5.9 (± 1.2)

CAPD: Children diagnosed with central auditory processing disorder, APM: Adult professional musicians, FEP: First episode psychosis adults.

between RGDT and GIN thresholds were seen collapsed across groups (RGDT and GINthres LE: $r = 0.39$, $p = 0.001$; RGDT and GINthresRE: $r = 0.36$, $p = 0.002$) (Figures 2 and 3). Excluding inconsistent cases, a significant correlation was found only between GINthresRE and GINthresLE ($r = 0.65$, $p < 0.0001$) collapsed across groups. Within group correlations, excluding inconsistent cases, showed significant correlations between GINthresRE and GINthresLE for the musicians and first episode psychosis patients (APM: $r = 0.74$, $p = 0.008$; FEP: $r = 0.73$, $p = 0.015$).

Discussion

Comparison of three groups' performance on two tests of temporal resolution revealed several interesting findings. A number of the children with CAPD and the adults with FEP presented inconsistent thresholds on the RGDT, a finding not seen for any individual in the two groups when tested on the GIN. In CAPD and FEP cases where the gap detection threshold could be calculated, participants obtained better thresholds for the GIN than the RGDT. Although the RGDT takes less time to administer because only one trial is presented for each gap interval between each pair of pure tones, while the GIN provides six trials for each specific gap duration, this speed of administration may have led to the inconsistencies seen on the RGDT, as well as the better gap thresholds on the GIN. Although the RGDT may be faster to administer, this advantage may be at the expense of reliability, given the frequency with which inconsistent or elevated thresholds are obtained. It could be argued that the most clinically used audiological test to acquire a threshold is the audiogram and threshold evaluation is not accomplished by providing one trial at each intensity presented. By providing six trials for each specific gap duration, the GIN offers a more robust psychoacoustic measure, consistent with signal detection theory which would predict that individuals might not detect every instance of an auditory event due to moment to moment variability in endogenous factors (e.g. attention, motivation, etc.), despite the stability of all external variables. Given the psychoacoustic definition of threshold as a proportion of hits (not 100% of hits), the design of the GIN enables a more accurate estimate of gap detection threshold. There is an extended version of RGDT which includes silent intervals larger than 40 msec between pairs of pure tones, which may be used when results using the shorter version are inconclusive. Unfortunately this extended version was not available for this study.

The decision to include the data from participants who presented inconsistent responses on the RGDT in the total number of failed results was made because we considered this inconsistent performance to reflect shortcomings in the psychoacoustic design of the RGDT (e.g. limited number of trials as noted above), which is relevant to the underlying question concerning differences between these two tests. Our finding of higher thresholds on the RGDT relative to the GIN has also been reported in normally-hearing children as well (Chermak & Lee, 2005). When inconsistent RGDT cases are

Table 2. Consistency & clinically failing for the RGDT & GIN. All numbers in this table represent number of cases per group and condition.

	RGDT	*GIN RE*	*GIN LE*
CAPD fails	19	6	6
CAPD inconsistent cases	13	0	0
CAPD consistent cases	9	22	22
CAPD total cases	22	22	22
FEP fails	17	8	12
FEP inconsistent cases	7	0	0
FEP consistent cases	10	17	17
FEP total cases	17	17	17
APM fails	0	0	0
APM inconsistent cases	0	0	0
APM consistent cases	11	11	11
APM total cases	11	11	11

RGDT: Random gap detection test. GIN RE: Gaps-in-noise right ears, GIN LE: Gaps-in-noise left ears, CAPD: Children diagnosed with central auditory processing disorder, APM: Adult professional musicians, FEP: First episode psychosis adults.

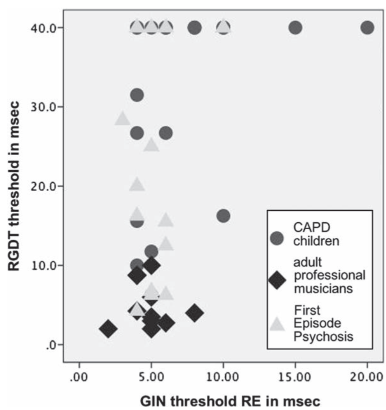

Figure 2. Correlations between RGDT and GIN thresholds (right ear).

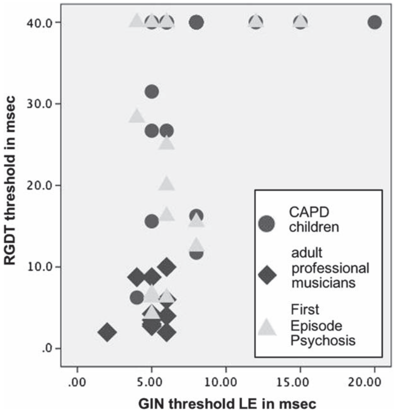

Figure 3. Correlations between RGDT and GIN thresholds (left ear).

excluded, mean RGDT thresholds differ significantly across the three groups, while GIN RE and LE do not. This might be interpreted as a difference in auditory function at the level of the brain stem across the three groups given Musiek et al's (2005) finding that the GIN is more sensitive to cortical compromise than brain stem involvement. It was not possible to ascertain the brain region of dysfunction of the children with CAPD using the behavioral battery of diagnostic tests described above. Taking all cases together (including inconsistent cases) both RGDT and GIN LE are significantly different across groups. By excluding inconsistent cases, the authors tried to minimize potential attention issues, although it is possible that excluding inconsistent cases might in fact be removing data of participants with the poorest temporal resolution. As shown in Table 1, excluding inconsistent RGDT cases reveals that the cases remaining tend to have lower/better GIN thresholds. The larger standard deviations for the RGDT compared with those of the GIN remain. Within each group statistically significant differences were seen between RGDT and GIN with better performance on the GIN than the RGDT and absence of inconsistent results on the GIN.

Our finding of a significant correlation between right and left ear GIN thresholds in the FEP group, is consistent with Musiek et al's (2005) findings of no significant ear differences on the GIN for their adult neurological group. The absence of a significant correlation between the GIN right and left ear thresholds in the CAPD group in the current study might be explained by the ongoing maturation of the central auditory nervous system which has been shown to produce ear differences in children on other central auditory measures (e.g. dichotic listening) (Moncrieff, 2011). Interaural differences in gap detection thresholds can only be documented using the GIN, as the RGDT is administered binaurally. GIN ear threshold differences were evident in all three groups tested in the present study.

The group of professional musicians was the only group with no temporal resolution thresholds exceeding 40 msec. They could distinguish more accurately with a lower threshold the silent intervals and this was evident for both the RGDT and the GIN. This was the only group for whom the mean RGDT and mean GIN thresholds approximated each other: the RGDT threshold and the GINthresLE were identical and the GINthresRE was slightly better (lower in value) than the RGDT. However, this was not statistically confirmed as thresholds of both tests (RGDT & GIN) were found to be statistically significantly different in the within group analysis. This was probably due to the fact that the distribution of the thresholds obtained for the RGDT is wider that the distribution of the thresholds obtained for the GIN. The musicians' superior performance is not surprising given expected better attention, and/or better executive function, and/or auditory processing skills relative to the other two groups (Parbery-Clark et al, 2013; Puschmann et al, 2013; Skoe & Kraus, 2013; Strait & Kraus, 2014), this finding despite the fact that the RGDT is not 'forgiving' (given one trial per gap duration) should a silent interval between a pair of pure tones be missed.

Regarding the true source of the musicians' performance in this study, Banai et al (2012) concluded that musicians' superior auditory temporal processing skills could not be attributed to attention and/or executive function, but was more likely the result of better processing of auditory information at a sensory level. They reached this conclusion based on the musicians' better performance in the fixed-context conditions, but equal performance in variable conditions. This led these researchers to the conclusion that based on their data and experimental design, musicians did not show increased ability across-trial variable contextual information; their better performance in the fixed condition could be explained by better auditory processing abilities through extensive training. Moreover, Banai & Yuval-Weiss (2013) concluded that prolonged development of auditory skills, when present, cannot be attributed to attention.

Given the purported influence of attention and other cognitive abilities in auditory processing testing (Moore et al, 2008; but see Weihing et al, 2013 for a different perspective), it is possible that differing cognitive demands across these two tests also influenced participants' performance and differences in thresholds obtained between tests across groups. Within-channel gap detection (as measured by the GIN) has been hypothesized (Phillips et al, 2010) to involve simple detection of neural activity discontinuity, and therefore would be less influenced by attention than the RGDT task involving counting (i.e. motor speech output, basic arithmetic reasoning, etc.). Moreover, attentional demands of the GIN are further reduced by the presentation of a number uttered before each noise section which might alert participants to attend to the possible upcoming gaps, in contrast to the RGDT where the participant hears specification of the pure–tone frequency to be tested followed by nine tone pairs. It should be mentioned that since we have been using tests whose utterances are spoken in English and are not particularly meaningful to the present participants (whose native language is Greek), the influence of the alerting utterances probably is minimal. Finally, it is possible that the participant's RGDT response in choosing between one or two tones heard, may be a decision dependent on processing involving auditory object (i.e. an acoustic experience that produces a two-dimensional image with frequency and time dimensions). (Griffiths & Warren, 2004). By contrast, the motor task required in response to detection of silence in an ongoing noise (GIN), may be based on more fundamental sensory processing experience.

Conclusions

In the present study, differences were seen on two temporal resolution tests, both between and within groups, in large part due to considerable differences in test design and norms. Mean thresholds for RGDT were larger than mean thresholds obtained for the GIN and a greater range of thresholds (larger standard deviations) was seen for the RGDT across all three groups as compared to the GIN, with a number of participants in both the FEP and CAPD groups presenting inconsistent results. The different outcomes obtained for the RGDT and the GIN within group are discussed in light of possible differences in auditory processing, attention across groups, and site of lesion. The GIN may be a truer measure of gap detection than the RGDT which may be confounding auditory fusion and auditory gap detection (Chermak & Lee, 2005). Lack of correlation between the two tests suggests that they measure different processes: the GIN measuring auditory gap detection and the RGDT possibly measuring some hybrid process requiring auditory fusion and gap detection.

Declaration of interest: The authors report no conflict of interest.

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