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Article *in* International Journal of Audiology · February 2011

DOI: 10.3109/14992027.2010.551217 · Source: PubMed

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International Journal of Audiology 2011; Early Online, 1–10

Original Article

An adaptive clinical test of temporal resolution: Within-channel and across-channel gap detection

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Abstract

Objective: Several methods exist to measure temporal resolution in a clinical setting. The Adaptive Tests of Temporal Resolution (ATTR©) are unique in that they incorporate an adaptive psychophysical procedure to present stimuli via computer sound card. The purpose of this study was to determine if ATTR gap detection thresholds (GDTs) were stable across presentation levels (80 dB SPL, listener-selected level) and sound cards (high-end, inexpensive). *Design:* GDTs were measured using three conditions of the ATTR: broad-band noise within-channel (BBN-WC), narrowband noise within-channel (NBN-WC), and narrowband noise across-channel (NBN-AC). Analysis of the acoustical properties of ATTR stimuli was made by measuring the electrical signals produced by each sound card. *Study Sample:* Participants were 30 young adults with normal hearing. *Results:* The ATTR GDTs did not differ between presentation levels for all three stimulus conditions. Also, neither ATTR stimuli nor ATTR GDTs differed between sound cards for all conditions. *Conclusions:* The ATTR may be used in a clinical setting with a relatively inexpensive sound card and listener-selected levels. Normative performance values for each ATTR condition are provided.

Sumario

Objetivo: Existen varios métodos en la clínica para medir la resolución temporal. La prueba adaptativa para la resolución temporal (ATTR@) es única en el sentido en que incorpora un procedimiento psico-físico para presentar estímulos por medio de una tarjeta de sonidos de una computadora. El propósito de este estudio fue determinar si los umbrales de detección de brechas (GDT) de la ATTR eran estables en diferentes niveles de presentación (80 dB SPL, nivel seleccionado por el oyente) y con diferentes tarjetas de sonido (hig-end, barata). *Diseño:* Los GDT fueron medidos en tres condiciones de ATTR: banda ancha, ruido en el canal (BBN-WC), ruido de banda angosta en el canal (NBN-WC) y ruido de banda angosta a través del canal (NBN-AC). El análisis de las propiedades acústicas de los estímulos de ATTR fue realizado midiendo las señales eléctricas producidas por cada tarjeta de sonido. *Muestra:* Los participantes fueron 30 adultos jóvenes con audición normal. *Resultados:* Los GDT ATTR no difirieron en los niveles de presentación en las tres condiciones de estímulo. Además, ni los estímulos de ATTR ni los GDT ATTR difirieron en con las diferentes tarjetas de sonido en todas las condiciones. *Conclusiones:* Los ATTR pueden ser utilizados en condiciones clínicas con una tarjeta de sonido relativamente barata y a niveles seleccionados por el oyente. Se proporcionan los valores normativos de desempeño para cada condición de ATTR.

Key Words: Temporal resolution; Gap detection; Within-channel; Across-channel

Auditory processing disorder (APD) involves a deficit in one or more of the following skills: sound localization and lateralization, auditory discrimination, auditory pattern recognition, temporal aspects of audition (including temporal integration, temporal discrimination, temporal ordering, and temporal masking), and auditory performance in the presence of competing or degraded acoustic signals (ASHA, 2005). According to this and other definitions (ASHA, 1996; Bellis, 2003; Chermak & Musiek, 1997), temporal aspects of auditory perception are an important part of the APD diagnosis. Thus, a standard component of the APD test battery is a test of auditory temporal resolution (Jerger & Musiek, 2000). Supporting the importance of temporal resolution is the often-cited link between temporal resolution deficits and poor recognition of speech, degraded by noise and reverberation in everyday listening environments, that is associated with sensorineural hearing loss and/or advancing age (e.g. Gordon-Salant & Fitzgibbons, 1993; Peters et al, 1998; Stuart & Phillips, 1996; Dubno et al, 2003). As difficulty understanding speech in noisy, reverberant environments is a common complaint of patients of all ages and degrees of hearing impairment, it is critical that clinical audiologists have tools for accurate and efficient assessment of temporal resolution across the lifespan.

Temporal resolution may be defined as the ability to follow and resolve rapid fluctuations in intensity and frequency over time (Lister et al, 2006). Assessment of temporal resolution includes, but is not limited to: gap detection/discrimination, duration discrimination, temporal order perception, and forward/backward masking. Although clinical tests targeting different areas of temporal resolution have been developed over the years (e.g. Zwicker, 1980; Zwicker & Schorn, 1982; Musiek

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(Received 21 October 2009; accepted 24 December 2010)

ISSN 1499-2027 print/ISSN 1708-8186 online
DOI: 10.3109/14992027.2010.551217

Abbreviations

AC	Across-channel
AFT-R	Auditory fusion test – revised
APD	Auditory processing disorder
ATTR	Adaptive tests of temporal resolution
BBN	Broad-band noise
GIN	Gaps-in-noise test
GDT	Gap detection threshold
HCL	Highest comfortable loudness
NBN	Narrow-band noise
RGDT	Random gap detection test
WC	Within-channel

et al, 2005), gap detection is the most common and well-studied test of temporal resolution. Gap detection is also the primary type of temporal resolution test available clinically today. To measure gap detection in a research laboratory setting, a listener is often presented with two (or more) sounds, one of which contains a silent gap. The listener is asked to identify which sound contained the gap. Stimulus choices for gap detection vary across gap detection tests but include broadband noise (BBN), narrowband noise (NBN), and pure tones.

Gap detection thresholds (GDTs) are known to be affected by a variety of stimulus parameters relevant to the present study, including stimulus bandwidth (Eddins et al, 1992; Snell et al, 1994), stimulus duration (He et al, 1999; Schneider & Hamstra, 1999), monotic, diotic, or dichotic presentation modes (Lister & Roberts, 2005; He et al, 1999, Gordon-Salant & Fitzgibbons, 1999), and the spectral similarity of the stimuli before and after the gap (Lister et al, 2002; Oxenham, 2000). There are advantages and disadvantages to using each of the popular types of GDT stimuli. BBN often provides the lowest thresholds and is effective for masking transient cues created by abruptly interrupting the stimulus with a silent gap. Moreover, Jerger and Musiek (2000) suggest using BBN stimuli for GDTs measured as part of the APD test battery. However, frequency-specific GDTs cannot be determined using BBN; BBN offers less flexibility in terms of the conditions that may be created and hypotheses that may be tested, and sloping hearing loss will limit the effective bandwidth of a BBN stimulus (e.g. Snell et al, 1994; Eddins et al, 1992). This last point is very important and not necessarily intuitive; reducing the audible bandwidth of the stimuli used to define a gap will reduce a listener's ability to detect the gap, particularly when it is the high frequency information that is removed. Therefore, for a clinical population with hearing loss of varying degree and configuration, BBN is not an appropriate stimulus for a gap detection task. For a clinical population of children with normal hearing and suspected APD, results with BBN stimuli may not be influenced by these known factors.

NBN offers greater flexibility than BBN in terms of test conditions and hypotheses that may be tested. One may create both within-channel (NBN-WC) conditions for which the stimuli before and after the gap are of the same frequency, and across-channel (NBN-AC) conditions for which the stimulus before and after the gap are of different center frequencies. In addition, NBN stimuli allow for measurement of GDTs in specific frequency regions as well as greater control of audibility. Because GDTs are generally poorer for NBN-AC conditions than NBN-WC (e.g. Grose et al, 2001; Lister & Roberts, 2005), and GDTs for the two types of conditions are not often correlated (Phillips & Smith, 2004), it is likely that detection of AC and WC gaps are served by different mechanisms of temporal processing. It is thought that WC gap detection is easier than AC gap detection because the former requires monitoring activity in a single neural 'channel' while the latter requires comparison of the relative timing between the offset of neural activity in one channel and the onset in an entirely different channel (Formby et al, 1998; Grose et al, 2001). At this point, it is not known which is more important for auditory communication; therefore, further study in a clinical setting with both WC and AC gap detection conditions is needed.

Emanuel (2002) found that the most frequently used test of gap detection was the auditory fusion test – revised (AFT-R; McCroskey & Keith, 1996). However, the AFT-R assesses perception of auditory fusion (i.e. the listener reports when two sound bursts are perceived as one) rather than gap detection (Chermak & Lee, 2005). Other than the AFT-R, tests of gap detection include psychophysical laboratory procedures, the revised AFT-R or random gap detection test (RGDT; Keith, 2000), and, more recently, the gaps-in-noise test (GIN; Musiek et al, 2005). In most laboratory measures of gap detection, a two- or three-interval, forced-choice adaptive psychophysical procedure is used along with laboratory hardware to control stimulus generation and response collection. While efficient and sensitive, these types of psychophysical laboratory procedures are not clinically feasible because of the complexity of the hardware and software required.

The random gap detection test (RGDT), like its predecessor, the AFT-R, is actually a test of auditory fusion. The RGDT includes several subtests in which tone burst or noise burst pairs are presented in a nine-item, single-interval, fixed (non-adaptive) procedure with randomly presented gap durations. The listener is required to report hearing one or two tone bursts or noise bursts. Specific norms are not provided for the subtests of the RGDT that use broadband noise bursts, although a normal range of 2–20 ms is suggested (Keith, 2000). Characteristics of the RGDT that may limit clinical utility include: (1) only nine stimuli are presented, each with a different gap duration; (2) the gap durations are spread over a relatively wide range (0, 2, 5, 10, 15, 20, 25, 30, 40 ms); (3) the observation intervals are unmarked with no feedback; (4) the performance level is undefined; and (5) a non-adaptive (fixed) procedure, a method of constant stimuli, is employed. It is established that adaptive methods provide greater control over response bias than fixed procedures (e.g. Taylor et al, 1983; Kollmeier et al, 1988). The RGDT instructions require listeners to label the single observation interval as one click or two clicks instead of comparing multiple stimulus intervals, and selecting the one with two stimuli as is often done in psychophysical laboratory procedures. Judgments may be relatively difficult for the RGDT due to this trial labeling, combined with observation interval uncertainty (Marshall & Jesteadt, 1986). This may be especially true for populations with phonological awareness, short-term memory, or certain cognitive deficits that make the labeling procedure or concept more difficult.

The gaps-in-noise test (GIN) uses BBN segments that are 6 s in duration with 0–3 randomly placed gaps per segment. Ten gap durations (2, 3, 4, 5, 6, 8, 10, 12, 15, and 20 ms) are available and each is repeated six times for a total of 60 gaps. The listener's task is to press a response button when a gap is detected. Gap detection threshold for the GIN is defined as the shortest gap that is detected on at least four of six presentations. Chermak and Lee (2005) suggested that the GIN may take more time to administer than the RGDT, but the relatively few trials presented for the RGDT may result in poor reliability. However, the GIN may also be subject to the previously-described labeling issues associated with RGDT and AFT-R.

The AFT-R, RGDT, and GIN are similar in that they are all designed to be presented via a CD player and routed through an audiometer, as are many other tests used in speech audiometry and APD batteries. Although commonplace, CD tests do not allow for easy implementation of the adaptive paradigms often used in laboratories to efficiently and accurately measure auditory perception. In contrast, such complex adaptive paradigms are quite easily administered using computer software. With computerized audiometers and software-driven hearing aid fittings in many clinical audiology practices today, the use of computer software for auditory assessment has become more feasible. Thus, previously-unavailable adaptive psychophysical paradigms may now be incorporated into standard clinical audiometry. The adaptive tests of temporal resolution (ATTR©) are an example of this.

The ATTR is a set of gap detection tests that have been shown to be valid, reliable, and clinically feasible (Lister et al, 2006). The ATTR is software designed to be used on a desktop computer with a sound card. Stimuli are stored offline in .wav format. The ATTR uses a 2I/2AFC adaptive procedure to measure gap detection thresholds (GDTs); two intervals of sound are presented and the patient uses a computer mouse to select the interval that contained a gap. Multiple conditions of BBN and NBN stimuli in both WC and AC configurations are available. Visual feedback is provided. Lister and colleagues (2006) provided normative data for the BBN-WC condition of the ATTR. In the present study we sought to expand upon our 2006 study by providing normative data for NBN and AC conditions as well as answer some basic questions regarding clinical utility.

One limitation of the ATTR, indeed for any software-driven assessment tool, is that presentation level is, in some clinical settings, controlled with the computer volume control – a level control which is not as precisely manipulated or calibrated as those on other audiometric equipment. Fortunately, there is evidence that presentation level, above a certain minimum sensation level, does not greatly impact GDTs. For listeners with normal hearing, gap thresholds do not appear to change with level increases above 25–30 dB SL (Shailer & Moore, 1983; Nelson & Thomas, 1997). Weihing and colleagues (2007) observed improved performance on the GIN with increases in sensation level up to 35 dB SL among young and middle-aged adults with normal hearing. Results were not different for GDTs and percent correct obtained at the highest presentation levels, 35 dB SL and 50 dB SL. Similar results have been found for young and middle-aged listeners with sensorineural hearing loss (Fitzgibbons & Gordon-Salant, 1987). Nelson and Thomas (1997) included loudness judgments in their study of the effects of level on gap detection. They found that, for young listeners with normal hearing, gap detection plateaued for levels judged as 'soft'. In contrast, for young and middle-aged listeners with hearing loss, gap detection plateaued for levels judged between 'comfortable' and 'loud'. Although the literature suggests that GDTs are not affected by stimulus level for levels above approximately 25–30 dB SL, it is not clinically feasible to measure thresholds for gap detection stimuli and then set output levels in dB SL before measuring GDTs. It is, however, feasible for a clinician to use the computer volume control and patient feedback to quickly set loudness level, a process which should be much faster than measuring a detection threshold for determination of dB SL.

Listeners are capable of making accurate and reliable loudness judgments (Cox, 1985; Leijon et al, 1984). Cox (1985) conceptualized an upper limit of comfortable loudness (ULCL), later revised to highest comfortable loudness (HCL; Cox, 1989), as the loudest sound pressure level comfortable to listen to for a long period of time. Cox (1985, 1989) found that, due to the use of relatively uncomplicated instructions provided for HCL measurement, most listeners will reliably establish very similar HCL values over multiple test sessions. NBN HCLs measured by Cox (1989) for young adults with normal hearing were approximately 85–90 dB SPL. For adults of undisclosed age with hearing loss, mean NBN HCLs were 103 dB SPL, approximately 30 dB above threshold for the same stimuli.

Presentation level has been demonstrated to have a negligible effect on GDTs above approximately 25–30 dB SL. HCLs are at or above this level and may be reliably measured. The ATTR is currently used with a fixed presentation level of 80 dB SPL, calibrated with a precision sound level meter. Experiment 1 of this study was designed to compare listener performance on the ATTR between a fixed, 80 dB SPL presentation level, and a patient-established highest comfortable loudness (HCL; Cox, 1985) which would only require equipment found in a non-laboratory, clinical setting. It is hypothesized that ATTR GDTs may be measured clinically at HCL without compromising performance. In Experiment 2, we compared listener performance (ATTR GDTs) and acoustic characteristics of ATTR stimuli using two different sound cards, representing the range of sound cards currently available.

Experiment 1

Method

Participants

Thirty young adults (three males), ranging in age from 20 to 37 years (mean = 25.2), participated in the study. All participants spoke English as a first language. All participants had pure-tone thresholds of ≤ 25 dB HL from 250 to 8000 Hz, including interoctaves 3000 and 6000 Hz, and tympanometry indicative of normal eardrum mobility. All participants reported no history of chronic otitis media, attention disorders, APD, speech-language disorders, neurologic disorders, neurologic medications, exposure to ototoxic drugs, or exposure to excessive noise. Participants were recruited from graduate and undergraduate classes at the University of South Florida (USF) and the USF community. Participants who were students were offered extra credit at the instructor's discretion, and all others were not compensated for their time.

Stimuli and instrumentation

The ATTR includes software written in Visual Basic™ v. 6.0 and is designed to run on a standard desktop or laptop PC. The software produces an adaptive two-interval, two-alternative, forced-choice psychophysical paradigm targeting 70.7% correct gap detection (Levitt, 1971). Thus, two intervals of sound are presented to the listener. In one interval (the standard interval), two noise bursts separated by a 1-ms gap are presented. This 1-ms standard gap is used to ensure that similar gating transients are present in both intervals (Lister et al, 2002; Phillips et al, 1997). In the other interval (the target interval), two noise bursts separated by a gap of adaptively varying duration are presented. The standard and target intervals are presented in random order. The listener's goal is to select the target interval. If the listener selects two target intervals (i.e. correct answer) in a row, the gap duration in the target interval is decreased by a factor of 1.2. If the listener selects the standard interval (i.e. incorrect answer) once, the gap duration in the target interval is increased by a factor of 1.2. For the BBN condition, the Gaussian noise bursts before and after the gap are 4 ms in duration. For the NBN conditions, the noise burst before the gap is 300 ms in duration, and the noise burst after the gap varies randomly in duration between 250 and 350 ms. Randomization of the duration of the stimulus after the gap has been shown to be the optimal method of controlling extraneous duration cues that can occur with fixed durations (Lister & Tarver, 2004). NBNs were quarter octave in bandwidth, geometrically centered on either 1000 Hz or 2000 Hz, and shaped with a $\cos^2$ window to create 1-ms rise-fall times on the offset of the first NBN and the onset of the second NBN (defining the gap). The onset of the first NBN and the offset of the second NBN were shaped with a $\cos^2$ window to create 10-ms rise-fall times. BBNs were unshaped.

ATTR stimuli are stored offline in .wav format (44100 Hz, 16-bit resolution) and limited to the 1–5 ms step size used in file creation. For gap durations between 1 and 100 ms, ATTR stimuli were created and stored with gaps in 1 ms steps. For gap durations between 102 and 200 ms, ATTR stimuli were created and stored with gaps in 2-ms steps. For gap durations between 205 and 400 ms, ATTR stimuli were created and stored with gaps in 5-ms steps. Gap durations longer than 400 ms were not created. The appropriate .wav file is selected within these limitations by the adaptive paradigm. For example, if the adaptive paradigm calculates a gap size $\geq$ 1.5 and $\leq$ 2.4, a 2-ms gap .wav file is played, and, if the paradigm calculates a gap size between 103.5 and 105.4, then a .wav file with a 104-ms gap is played.

The BBN was used to create a within-channel condition (BBN-WC) with BBN bursts before and after the gap. The two NBNs were used to create a within-channel condition (NBN-WC) with 2000-Hz NBNs defining the gap and an across-channel condition (NBN-AC) with a 2000-Hz NBN before the gap and a 1000-Hz NBN after the gap. Oxenham (2000) and Roberts and Lister (2004) found that GDTs measured monotically and diotically among young adults with normal hearing are not significantly different, so diotic presentation was chosen for this experiment.

Stimuli were presented through a LynxOne (Lynx Studio Technology) sound card and Sennheiser Model HD265 linear circumaural earphones. For this study, a Tucker-Davis Technologies (TDT; Alachua, USA) programmable attenuator (model PA5) was added to the standard ATTR setup. This was only included to facilitate verification of presentation levels for the current investigation and is not a standard component for clinical testing. Calibration was confirmed at the beginning and end of the study using a Brüel & Kjær Type 2250 sound level meter, and daily by making sure the computer volume control and TDT hardware were set to the appropriate output level.

Procedures

During all procedures, listeners were seated in a quiet room facing a desktop computer, wearing earphones connected to the computer sound card. The HCL presentation level for each stimulus (BBN, 1000 Hz NBN, 2000 Hz NBN) was established prior to GDT measurement. Then, GDTs were measured for the three stimulus conditions (BBN-WC, NBN-WC, NBN-AC) at two presentation levels (fixed 80 dB SPL, listener-selected HCL). Type of stimulus and presentation level was randomized.

HCL presentation levels were established manually using the procedure described by Cox (1985) for each of the three ATTR stimuli. The ATTR software was adapted for this purpose and a new module was included to allow presentation of 4-ms BBN bursts, 300-ms 1000 Hz NBN bursts, and 300-ms 2000 Hz NBN bursts individually. For the HCL procedure, a starting level estimated to be between 20–40 dB SL that is described by the patient as 'comfortable' is recommended. We chose to begin by estimating detection threshold for the individually presented BBN or NBN stimuli. The participant was instructed to face away from the computer as the experimenter manually adjusted the TDT attenuator until threshold was estimated using a modified Hughson-Westlake procedure. Then, as recommended by Cox, the level was increased by 20–40 dB and in 10–15 dB steps thereafter until the participant noted that the stimulus was no longer comfortable for long-term listening. At that point, the level was decreased in 5-dB steps until the participant reported that the stimulus was again comfortable. Next, the level was increased in 5–15 dB steps until no longer comfortable. The participant was told that the level sought was not the 'perfect' loudness, but a level that would be on the louder side of acceptable for long-term listening (Cox, 1985). Attenuator values were recorded for both the threshold and the HCL conditions and were then converted to dB SL and dB SPL at a later time. Although an external attenuator was used in the present study so that presentation levels could be easily and precisely determined and analysed, it is expected that the computer volume control will be used in the clinical setting. This procedure required approximately three minutes to complete.

GDTs were measured for each participant and condition using the three ATTR stimulus conditions and the two presentation levels. Participants were instructed that they would hear two noise bursts. For BBN, they were told they would hear two intervals that sounded like clicks (pops), and for NBN, they were told they would hear two intervals that sounded like noise. They were instructed that their goal was to select the interval with the gap and, if both intervals seemed to have a gap, they should select the interval with the larger gap. Participants indicated their response by using a computer mouse, and were given visual feedback.

Before the first run of each new stimulus (BBN-WC, NBN-WC, and NBN-AC), three correct trials of large-gap practice were required. Large-gap practice included: 15-ms gaps for BBN-WC, 100-ms for NBN-WC, and 300-ms for NBN-AC. If the practice trial responses were not correct, the participant was re-instructed and the practice trials were repeated until the participant responded correctly to three practice trials in a row. Following practice, a minimum total of 18 runs were completed (three stimulus conditions, two presentation levels, three runs per condition). Runs were repeated if stopping criteria were not met for a particular condition. Stopping criteria for BBN-WC were three GDTs within $\pm$ 2 ms, and for NBN-WC and NBN-AC, criteria were three GDTs within a factor of two. For each run, GDTs were calculated as the geometric mean of the final six reversals of the total eight reversals in the adaptive procedure (Lister et al, 2006). Conditions were presented in random order. Each adaptive run required approximately one to two minutes to complete.

Results

HCLs are presented in Table 1. Sensation levels corresponding to the HCLs for the ATTR stimuli were at or above the values at which GDTs cease to be affected by manipulation of presentation levels and varied from a low of 30 dB SL (P26) for the BBN to a high of 75 dB SL (P10, P27, P28) for the 2000-Hz NBN. Within-stimulus ranges of HCLs were consistent across stimuli at ~30–35 dB, and were similar to those reported by Sammeth et al (1989) for MCLs for speech stimuli (~27 dB). Sound pressure levels corresponding to the HCLs were close to the 75–80 dB values often used in psychophysical laboratory measurements of gap detection, providing confirmation that those often-used levels are, indeed, comfortable.

A one-way analysis of variance (ANOVA) indicated that HCLs in dB SPL differed significantly across conditions [$F(2,58) = 3.472$, $p = 0.038$]. An LSD post-hoc analysis showed that only BBN and 1000-Hz NBN HCLs differed significantly ($p = 0.029$). HCLs in dB SL also differed significantly across conditions [$F(2,58) = 23.36$, $p < 0.0001$] with HCLs for all three stimulus conditions significantly different from each other ($p < 0.013$ for all comparisons).

Table 1. Individual HCLs expressed in dB SL and dB SPL. Mean HCLs with standard deviations in parentheses are shown in the bottom row.

	dB SL			*dB SPL*		
Participant	*BBN*	*2000 Hz NBN*	*1000 Hz NBN*	*BBN*	*2000 Hz NBN*	*1000 Hz NBN*
P01	35	50	60	60	65	85
P02	55	70	60	70	80	80
P03	55	60	60	75	70	80
P04	55	60	50	75	70	65
P05	55	65	60	70	75	75
P06	55	60	55	80	75	75
P07	55	70	55	70	80	75
P08	60	65	60	80	75	80
P09	55	65	55	75	75	75
P10	65	75	65	80	85	85
P11	40	60	60	70	80	80
P12	65	65	60	80	80	80
P13	55	60	55	85	75	75
P14	60	60	60	80	75	80
P15	40	60	55	65	75	75
P16	60	65	60	85	80	80
P17	65	60	55	80	75	80
P18	60	65	65	80	85	85
P19	60	60	65	80	75	85
P20	50	60	55	65	75	75
P21	50	55	50	75	75	75
P22	50	60	65	70	70	75
P23	60	70	60	85	85	85
P24	65	60	60	85	75	80
P25	60	70	65	80	85	85
P26	30	45	40	50	60	60
P27	60	75	70	80	90	90
P28	60	75	60	80	85	80
P29	60	70	65	80	80	85
P30	65	70	65	85	80	80
Mean (SD)	55.3 (8.75)	63.5 (6.85)	59.0 (5.83)	75.8 (8.07)	77.0 (6.27)	78.8 (6.01)

This supports the establishment of HCL for each stimulus condition prior to GDT measurement.

Mean GDTs measured for each presentation level and stimulus condition are shown in Figure 1. The expected and well-documented difference between WC and AC conditions is shown with AC GDTs approximately eight times larger than WC GDTs. The two types of WC GDTs (BBN and NBN) do not appear to differ. GDTs also appear highly similar across presentation levels.

A two-way ANOVA indicated that GDTs differed significantly by stimulus condition [$F(2,58) = 137.84$, $p < 0.001$] but not by presentation level [$F(1,29) = 0.07$, $p = 0.792$]. The interaction between stimulus condition and presentation level was not significant [$F(2,58) = 0.235$, $p = 0.791$]. An LSD post-hoc analysis of the significant condition effect showed that NBN-AC GDTs were significantly larger than both BBN-WC and NBN-WC GDTs ($p < 0.001$), but BBN-WC and NBN-WC did not differ significantly ($p = 0.974$). The WC GDTs were similar to or somewhat smaller than those measured previously, and AC GDTs were somewhat larger than those measured previously (e.g. Lister et al, 2002; Roberts & Lister, 2004; Lister & Roberts, 2005; Phillips et al, 1997; Formby et al, 1993). The lack of a presentation level effect supports the use of listener-selected HCL levels with the ATTR in a clinical setting.

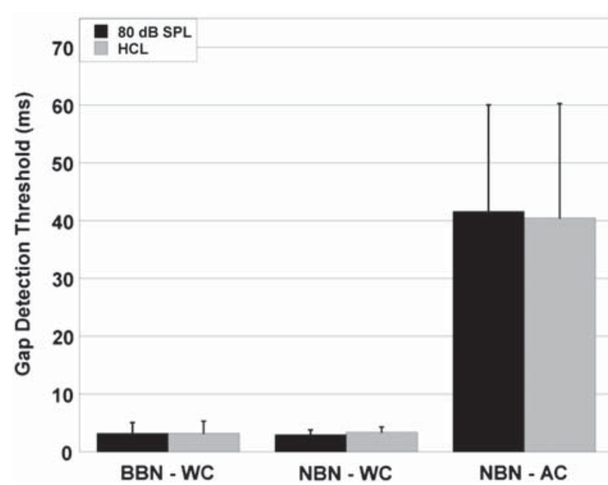

Figure 1. Mean ATTR GDTs are shown for each stimulus condition (x-axis) and presentation level condition (black and gray bars). BBN refers to broad-band noise. NBN refers to narrow-band noise. WC refers to within-channel, and AC refers to across-channel. HCL refers to highest comfortable loudness. Standard deviation bars are shown.

Experiment 2

Another issue of consideration that relates to clinical implementation of the ATTR is the variety of sound cards used in desktop computers. The ATTR was developed with a high-end and relatively expensive sound card (LynxOne by Lynx Studio Technology, ~US$500) with distortion-minimizing logic. This type of sound card may not be available in many audiology facilities so it was important to determine if similar stimulus presentation and temporal resolution results could be obtained with a lower quality sound card. Although price does not always correspond to quality, as an initial step we chose to determine if use of a less-expensive sound card that does not have the features of the LynxOne would affect the ATTR. Therefore, the purpose of Experiment 2 was to compare listener performance (ATTR GDTs) and acoustic characteristics of ATTR stimuli using two different sound cards, representing the range of sound cards currently available. The sound cards used were the LynxOne (Lynx Studio Technology), the sound card used previously with the ATTR and in Experiment 1, and the relatively less expensive and widely-available Montego 7.1 Dolby Digital Live (Turtle Beach, ~US$60) sound card. As may be observed from the specifications for each sound card (Appendix A and B: supplementary appendices to be found online at: http://informahealthcare.com/doi/abs/10.3109/14992027.2010.551217), the level of detail provided was very different between sound cards. Such variability makes sound card selection for auditory perceptual assessment difficult.

First, an analysis of the acoustic properties of each of the three stimulus conditions was completed. Two trials for each stimulus condition were played out of each sound card and the electrical signal was recorded using the analog input of the same sound card. Recordings were then repeated and compared within sound card and between sound cards. Next, GDTs were measured for the three ATTR stimulus conditions using the Turtle Beach sound card and these were compared to the GDTs already measured in Experiment 1 using the LynxOne card. The participants, ATTR stimulus conditions, and procedure for GDT measurement were identical to those described for Experiment 1 except that stimuli were presented at the fixed, 80 dB SPL level only in an effort to exert greater stimulus control.

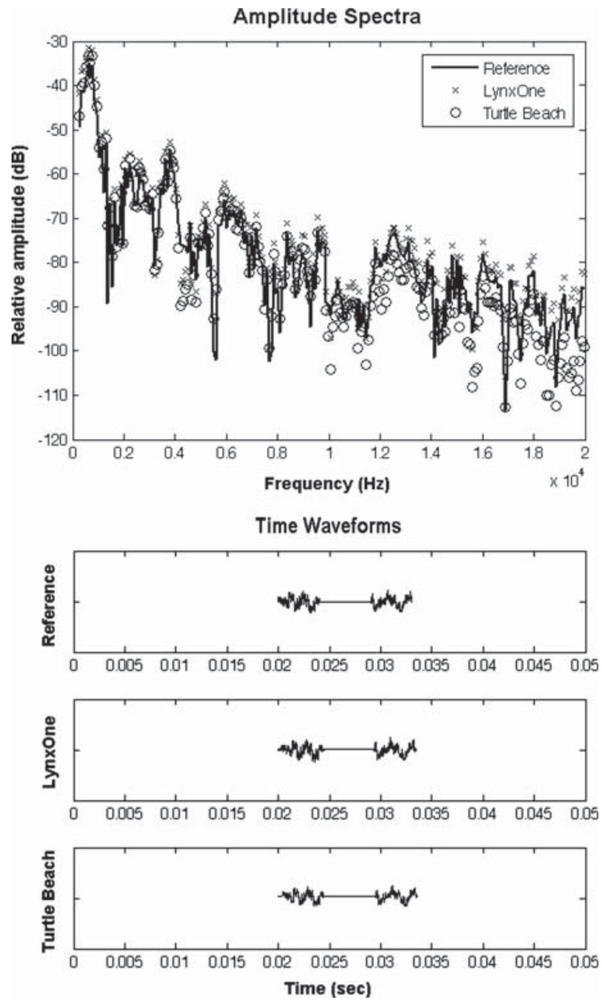

Figure 2. Top: Spectra of BBN-WC stimuli (4-ms Gaussian noise bursts) for the original (reference) .wav file and the .wav files as played through LynxOne and Turtle Beach sound cards. Bottom: BBN waveforms with a 5-ms gap for the reference and the LynxOne and Turtle Beach sound cards.

Results

Acoustic analysis

The spectrum, waveform, and gap duration for all three stimulus conditions were examined. Spectra showed small differences across frequencies for BBN-WC (Figure 2), NBN-WC (Figure 3), and NBN-AC (Figure 4). In Figure 2, small differences in the BBN are visible across the frequency range but, upon examination of multiple tokens of BBN for each sound card, these differences appear to be random. For the two NBN conditions, spectral differences are minimal and appear distant from the center frequency of the NBN stimuli. Waveforms appear equivalent for both sound cards in all conditions. Differences observed between sound cards were no greater than the differences observed within each sound card. Gap duration was matched within 1 ms for all stimulus conditions.

GDTs

ATTR GDTs for each sound card and stimulus condition are shown in Figure 5. GDTs appear highly similar for the two sound cards in the BBN-WC and NBN-WC conditions and appear slightly higher for the Turtle Beach than the LynxOne card in the NBN-AC condition. A two-way ANOVA indicated that the effect of sound card was not significant [$F(1,29) = 1.186$, $p = 0.285$], and the stimulus condition effect observed in Experiment 1 was present for both sound cards [$F(2,58) = 131.14$, $p < 0.001$]. The interaction between stimulus condition and sound card was not significant [$F(2,58) = 1.32$, $p = 0.274$]. This suggests that use of a relatively less expensive sound card does not compromise ATTR acoustics or performance.

General discussion

Our previous work (Lister et al, 2006) established the clinical utility of, and provided normative values for, a BBN-WC condition of an adaptive gap detection test controlled by software and presented through a computer sound card. The purpose of the present study was to expand upon that work by examining the utility of, and providing normative values for NBN-WC and NBN-AC conditions. To that end, two experiments were conducted. First, we examined the effect of supra-threshold level manipulation on ATTR GDTs to determine if a listener-selected presentation level would be appropriate for clinical use. If so, expensive calibration equipment would

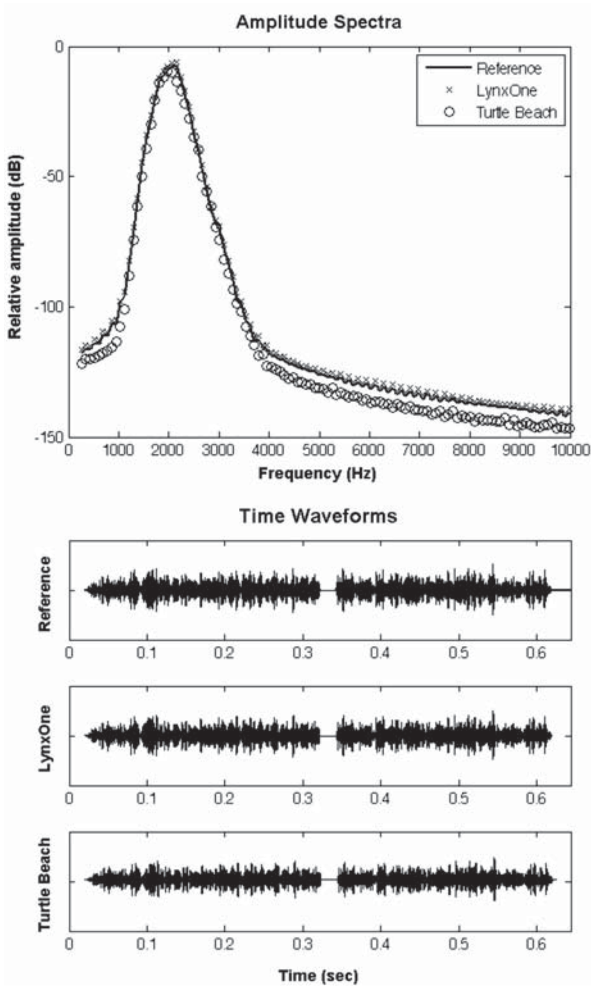

Figure 3. Top: Spectra of narrowband noise within-channel (NBN-WC) stimuli (quarter octave, 2000 Hz center frequency, 250–350 ms) for the original .wav file (reference) and the .wav files as played through the LynxOne and Turtle Beach sound cards. Bottom: NBN-WC waveforms with a 20-ms gap for the reference and the LynxOne and Turtle Beach sound cards.

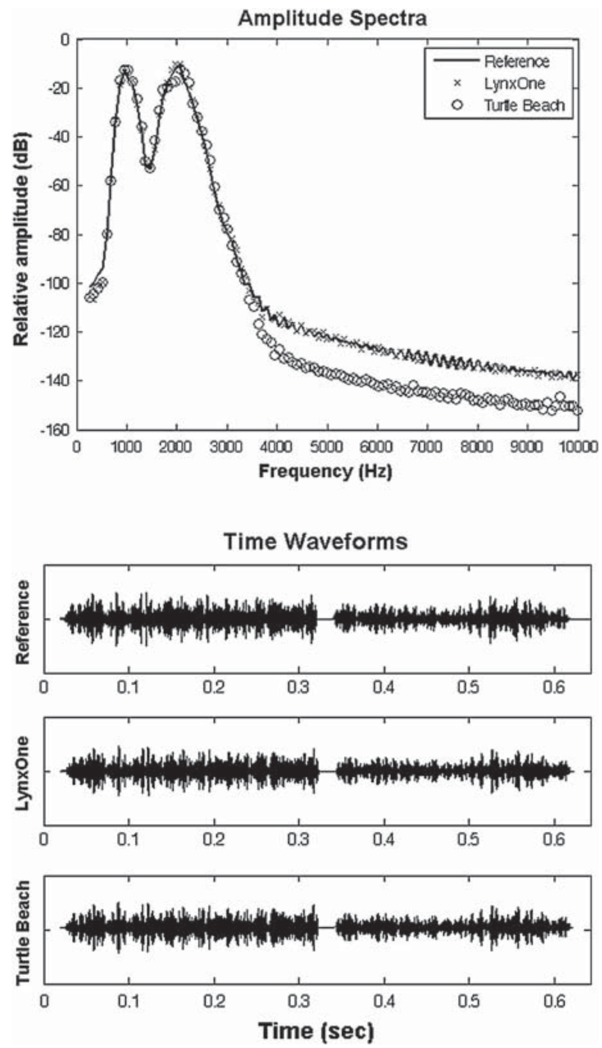

Figure 4. Top: Spectra of narrowband noise across-channel (NBN-AC) stimuli (quarter octave, 2000 and 1000 Hz center frequencies, 250–350 ms) for the original .wav file (reference) and the .wav file as played through the LynxOne and Turtle Beach sound cards. Bottom: NBN-AC waveforms with a 20-ms gap for the reference and the LynxOne and Turtle Beach sound cards.

not be necessary to set ATTR levels in the clinical setting. Second, we compared stimuli and ATTR GDTs using two soundcards, LynxOne and Turtle Beach, representing two extremes of the sound card price spectrum. If stimuli and performance were similar across sound cards, then a high-performance sound card would not be necessary for ATTR use.

The BBN-WC GDTs measured in the present study ranged from 1 to 11 ms (mean = 3.2 ms) and were consistent with those reported by Lister and colleagues (2006; range = 1–7 ms, mean = 2.2 ms); by Roberts and Lister (2004; range = 1–5 ms, mean = 2.5 ms); and others (mean = ~2–3 ms; Plomp, 1964; Phillips et al, 1998). In the present study, the NBN-WC GDTs ranged from 1 to 5 ms (mean = 3.2 ms). These are slightly smaller than those measured by Lister and Roberts (2005; range = 3–9 ms, mean = 5.5 ms) and Phillips and colleagues (1997; range = ~5–6 ms, mean = ~5.5 ms), and they are much smaller than those measured by Lister and colleagues (2002; range = 5–46, mean = 15). In the present study, the NBN-AC GDTs ranged from 12 to 121 ms (mean = 42.6 ms). These are slightly larger than those measured by Lister and Roberts (2005; range = 8–76 ms, mean = 31 ms), and Lister and colleagues (2002; range = 15–58 ms; mean = 30 ms), and they are much larger than those measured by Phillips and colleagues (1997; range = ~10–25 ms, mean = ~15 ms).

Differences across studies could be attributed to differences in equipment used to generate and control the markers. Lister and colleagues (2002) used a Krohn-Hite Corporation Model 390B multichannel filter and Tucker-Davis Technologies (TDT; Alachua, USA) System II hardware and software to generate, manipulate, and present the stimuli. Roberts and Lister (2004) and Lister and Roberts (2005) used a combination of TDT System II and System III to both generate and control the stimuli. The ATTR markers were generated using TDT System III and silent gap durations were manipulated using Adobe Audition (version 1.5) software. Subsequent sound files were stored offline in .wav format. It is possible that these differences in hardware and software altered the stimuli through: (1)

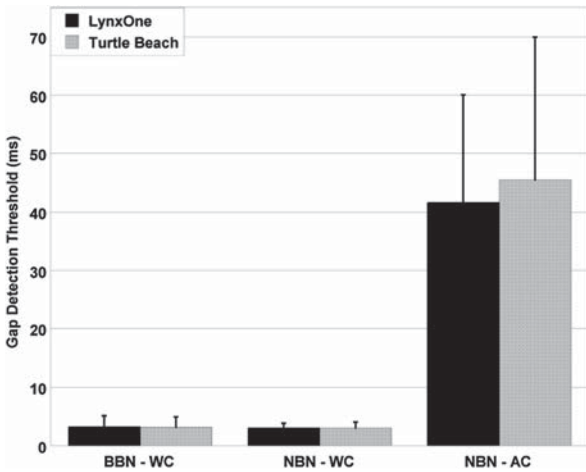

Figure 5. Mean gap detection thresholds (GDTs) for the three ATTR conditions (x-axis) and the LynxOne and Turtle Beach sound cards (black and gray bars). BBN refers to broad-band noise. NBN-WC refers to narrow-band noise within-channel. NBN-AC refers to narrow-band noise across-channel. Standard deviation bars are shown.

variations in accuracy of digital to analog conversion; (2) temporal or spectral alteration of analog signals; or (3) alteration of electrical stimuli by different headphones.

Results revealed no significant differences in GDTs between presentation levels or sound cards. Also, the acoustic parameters of ATTR stimuli were highly similar between sound cards. This is in agreement with the literature (Shailer & Moore, 1983; Fitzgibbons & Gordon-Salant, 1987; Nelson & Thomas, 1997; Weihing et al, 2007) and our hypothesis that manipulation of stimulus level well above approximately 25–30 dB SL would not affect ATTR GDTs. Recall that the literature indicates HCLs are typically at or above 30 dB SL (Cox, 1985, 1989). These results suggest that the ATTR may be used in a clinical audiology setting with a common, affordable sound card and listener-selected levels; no complex calibration is required.

As expected, GDTs were larger for NBN-AC (~43 ms) than NBN-WC (~3 ms) and BBN-WC (~3 ms). As a result of the somewhat smaller NBN-WC thresholds and larger NBN-AC thresholds measured in the present study, the mean difference between NBN WC and AC conditions in the present study (~40 ms) was larger than that of Lister and colleagues (2002; ~15 ms), Lister and Roberts (2005; ~26 ms), and Phillips and colleagues (1997; ~10 ms). Most interesting and useful was the finding that the two WC conditions did not produce different results. In fact, the mean GDTs for these two conditions are identical (3.2 ms). This suggests that both BBN and NBN may be used interchangeably to measure WC gap detection among young adults with normal hearing and negative histories of chronic otitis media, APD, exposure to ototoxic drugs or excessive noise, or disorders of speech-language, attention, or neurologic function. This finding should be interpreted cautiously, however. As mentioned earlier, there are potential limitations to using BBN stimuli to measure gap detection: inability to measure frequency-specific GDTs, limited ability to measure across-channel GDTs, and theoretical interaction between sloping hearing loss and audible bandwidth of the BBN (e.g. Snell et al, 1994; Eddins et al, 1992). Certainly for clinical populations with sloping hearing loss for which audible bandwidth of a BBN stimulus will vary widely, a BBN-WC condition may not be the best choice for measuring within-channel temporal resolution. A NBN-WC condition like the one provided by the ATTR may be a better choice for this population, but more research is needed. Specifically, although some control over extraneous spectral cues was executed by using a 1-ms gap in the standard interval, qualitative differences between the spectral cues available in the standard and target intervals could have existed for the NBN-WC condition. Such a possibility remains to be explored.

Mean GDTs and standard deviations are shown in Table 2 for this group of young adults with normal hearing. Lister and colleagues (2006) found mean ATTR BBN-WC GDTs of 2.2 ms (*s.d.* = 1.3) for the same population, consistent with the values in Table 2.

Jerger and Musiek (2000) suggested a minimum APD test battery that included temporal gap detection as a key component. Emanuel (2002) found that none of the audiologists who participated in her survey used the minimum APD protocol provided by Jerger and Musiek (2000). Gap detection testing was one of the tests regularly omitted from the APD test battery. This suggests a need for a clinical test of gap detection that could be included if shown to have desirable sensitivity to and specificity for the disorder in question. Very few clinical tests of gap detection exist, as reviewed in the introduction. Of these, the ATTR is unique in that it allows efficient measurement of GDTs using an adaptive paradigm and offers both BBN and NBN stimuli in within-channel and across-channel conditions.

There are several benefits of using the ATTR to measure GDTs to assess temporal resolution. First, stimuli are stored offline and do not require special hardware to be generated and played. Second, the ATTR uses an adaptive procedure which allows most of the measurements to be made close to the GDT. Third, the ATTR is reliable across runs and requires a short amount of time to administer; each run takes approximately one to two minutes. Finally, the ATTR is easy for clinicians to administer. The clinician enters patient information and initiates the test. From there, the ATTR presents the stimulus to the patient and tracks the patient's responses. At the end of each run, the patient's GDT is displayed and may be recorded or printed by the clinician.

Clinically abnormal ATTR results may be interpreted as a deficit in temporal resolution, decrement detection (i.e. intensity resolution), or both. Indeed, Plomp (1964) suggested that the detection of a within-channel gap depends on the strength of the response to the onset of the marker after the gap as well as the suppression of activity following the offset of the marker before the gap. Ongoing studies in multiple sites are focused on clinical populations, including children, older adults, individuals with hearing loss, and individuals with lesions of the central auditory nervous system. Specific stimulus parameters are also being investigated including marker duration, marker bandwidth, and presentation paradigm.

Summary and Conclusions

The primary purpose of this study was to compare ATTR GDTs measured at two supra-threshold presentation levels and measured using two sound cards. The acoustic parameters of the ATTR stimuli

Table 2. Mean ATTR GDTs for each stimulus condition for the participants in this study. GDTs were averaged across presentation level and sound card condition. Standard deviations are shown in parentheses.

	BBN-WC	*NBN-WC*	*NBN-AC*
Young adults with normal hearing	3.2 (1.9)	3.2 (0.9)	42.6 (20.8)

were also compared across sound cards. A secondary purpose was to provide normative data for ATTR NBN conditions, including both within-channel and across-channel GDTs. Results indicated that (1) GDTs are equivalent at a fixed 80 dB SPL presentation level and at a listener-selected HCL for both within-channel and across-channel stimulus conditions; (2) GDTs are equivalent for two sound cards, representing the range of current sound card technology, for both within-channel and across-channel stimulus conditions; (3) acoustic parameters of ATTR stimuli are equivalent between sound cards for all stimulus conditions; and (4) NBN-AC GDTs are larger than NBN-WC and BBN-WC GDTs, while NBN-WC and BBN-WC GDTs do not differ. These results suggest that a listener-selected HCL presentation level and the Turtle Beach (Montego 7.1 Dolby Digital Live) sound card, when used with the ATTR, provide results that are as valid as those obtained using a fixed 80 dB SPL presentation level and the LynxOne (Lynx Digital Studios) sound card. Also, it may be possible to use BBN-WC and NBN-WC conditions interchangeably to assess WC gap detection in a normal-hearing population, although more research is needed. We currently recommend the NBN-WC for assessment of WC gap detection in patients with sloping hearing loss due to the influence of audible bandwidth on GDTs. The ATTR is a very accessible and affordable clinical tool for the assessment of temporal resolution; the only necessary equipment is a desktop computer, the ATTR software, and a sound card.

Acknowledgments

Portions of the data presented in this article were presented at the Florida Academy of Audiology meeting in Orlando, and the American Academy of Audiology convention in Charlotte in 2008.

Declaration of interest: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper. The Adaptive Tests of Temporal Resolution (ATTR) is not a commercial product sold for profit; it is available at no charge from the developers, Drs. Lister and Roberts.

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Supplementary material available online

Appendix

Specifications for each sound card used in experiment 2 (Appendices A and B) are to be found online at: http://informahealthcare.com/10.3109/14992027.2010.551217