Correlations between otoacoustic emissions and performance in common psychoacoustical tasks

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Performance was measured on seven common psychoacoustical tasks for about 75 highly trained subjects. Because some psychoacoustical outcomes varied by race, the subjects were partitioned into White and Non-White categories for analysis. Sex, race, and menstrual-cycle differences in performance are described in a companion paper [McFadden, Pasanen, Maloney, Leshikar, and Pho (2018). *J. Acoust. Soc. Am.* **143**, 2338–2354]. Also measured for all subjects were three types of otoacoustic emissions (OAEs): spontaneous otoacoustic emissions (SOAEs), click-evoked otoacoustic emissions (CEOAEs), and distortion-product otoacoustic emissions (DPOAEs). The experimental question was whether and how OAEs were correlated with psychoacoustical performance. In accord with past findings, the SOAEs and CEOAEs exhibited substantial sex and race differences, but the DPOAEs did not. Somewhat surprisingly, the correlations between OAEs and psychoacoustical performance were generally weak. No form of OAE was highly correlated with any psychoacoustical task for both sexes within a race category. Thus, there was no compelling evidence that the mechanisms underlying OAEs also contribute systematically to performance in any of the simultaneous or temporal masking tasks studied here. Especially surprising were the weak correlations between OAEs and detection of a tone in the quiet. Apparently individual differences in psychoacoustical performance reside more in post-cochlear (neural) mechanisms than in individual differences in the cochlear (“mechanical”) mechanisms underlying the OAEs measured here.

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I. INTRODUCTION

Soon after the discovery of otoacoustic emissions (OAEs; see Kemp, 1978, 1979), investigators began to wonder what, if anything, they contributed to everyday hearing. Because little is yet known, a large-scale study was implemented to determine how the individual differences in OAEs covary with performance on a number of common psychoacoustical tasks. Also of interest were sex and menstrual-cycle differences. Subjects were tested psychoacoustically in crews of 6–8. For each crew of listeners, performance was measured daily for seven different psychoacoustical tasks over the course of several weeks, and for the female subjects, the daily data were partitioned according to the phase of the menstrual cycle. OAEs were measured individually during the course of employment, multiple times for the female subjects. Here we report the correlations between various OAE and psychoacoustical measures; elsewhere we report on the basic psychoacoustical data acquired (McFadden *et al.*, 2018). A third report is in preparation on psychoacoustical performance and auditory evoked potentials (AEPs), which also were measured in this study.

Some work has been done on relating OAEs to psycho-physical tasks other than simple hearing sensitivity (e.g., Probst and Harris, 1996; Neumann *et al.*, 1997; Smurzynski and Probst, 1999), and while interesting, that work did not involve tasks selected for their apparent dependency on the cochlear mechanisms responsible for OAEs, the tasks were few, and the subjects were largely unselected. The tasks chosen for this study had previously been linked to the process of cochlear amplification (discussed in McFadden *et al.*, 2018).

One impetus for the interest in sex differences in psychoacoustical tasks was the well-established existence of sex differences in OAEs. Females were shown to have more spontaneous otoacoustic emissions (SOAEs; see Bilger *et al.*, 1990; Burns *et al.*, 1992; Talmadge *et al.*, 1993; McFadden and Pasanen, 1999) and stronger click-evoked otoacoustic emissions (CEOAEs; see McFadden and Pasanen, 1998). The sex differences that do exist for distortion-product otoacoustic emissions (DPOAEs) are smaller than those for SOAEs and CEOAEs (reviewed in McFadden *et al.*, 2009a). The existence of sex differences in the OAEs of newborns as well as in adults (Strickland *et al.*, 1985; Burns *et al.*, 1992), and the apparent stability of OAEs through life (Burns, 2017) suggest that OAEs are permanently influenced by prenatal events, likely hormonal events (reviewed by McFadden,

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2002, 2008, 2011). In accord with this idea are results from various non-human species that were exposed to atypical hormone levels prenatally (e.g., [McFadden et al., 2009b](#)). Also, the results from studies on various special populations of humans are of interest in this context ([McFadden, 2002, 2008, 2011](#)). (For sex and hormonal differences in additional species, see [Bass et al., 2016](#).)

Sex differences in psychoacoustical performance have been less well studied than sex differences in OAEs ([McFadden, 1998](#)). As reported elsewhere ([McFadden et al., 2018](#)), some of the seven psychoacoustical tasks reported here did exhibit sex differences. An unexpected outcome was that sex differences interacted with race differences for many of our tasks. For example, detection of a 3.0-kHz tone in the quiet showed no obvious sex difference when our subjects were pooled across race, but when they were partitioned into Non-White and White categories, a substantial sex difference did emerge for the latter group. Once race differences were noticed, all our analyses were changed to incorporate this factor. Accordingly, the correlations reported here between OAEs and psychoacoustical tasks are presented both pooled across and partitioned by race. Because substantial sex differences exist for OAEs, all correlations between OAEs and psychoacoustical task were calculated within sex. Race/ethnic differences previously had been reported for various behavioral and physiological auditory measures (see discussion in [McFadden et al., 2018](#)).

The auditory literature contains both behavioral and physiological studies showing an effect of the menstrual cycle (reviewed by [McFadden, 1998](#), and [McFadden et al., 2018](#)). The differences across menstrual phase suggest that circulating levels of hormones can temporarily alter some relevant mechanisms in the cochlea or auditory brain. A common finding was that females were most like males during menses, when both estrogen and progesterone are low. For our seven psychoacoustical tasks, these effects were small and invariably not statistically significant ([McFadden et al., 2018](#)). Even so, here we sometimes report separate correlations for the menses and midluteal phases of the cycle, as well as after pooling the data over the cycle.

We wish to emphasize two points made elsewhere ([McFadden et al., 2018](#)) about sex and race differences. The authors' position is that *differences are not deficiencies*, and no reader should conclude otherwise from our reports. The group differences we have observed typically are small in stimulus units and thus are of little everyday importance. Rather, our sex and race differences are primarily informative about underlying mechanisms affecting the auditory system—hormonal, genetic, pigmentation, and other mechanisms. Second, the authors regard the common categories used for race to be a poor proxy for what we believe to be the actual basis for our apparent “race” differences: individual differences in pigmentation. This point is discussed in Sec. IV B.

Again, the primary goal of this report is to examine the correlations between different types of OAE and performance in several common psychoacoustical tasks for listeners with normal hearing. Might the individual differences in OAEs covary with the individual differences in psychoacoustical performance for some tasks?

II. METHODS

To repeat, one of the goals of this study was to measure sex and menstrual-cycle differences in well-trained subjects for a number of psychoacoustical tasks, and those results are reported in [McFadden et al. \(2018\)](#). Another goal was to determine if performance in any psychoacoustical task was correlated with some measure of OAEs, and those are the data reported here. This Methods section is intentionally brief. Additional general facts and specific details can be found in [McFadden et al. \(2018\)](#).

All aspects of this study were approved by the Institutional Review Board of The University of Texas, Austin.

A. Subjects

Subjects were primarily college students, who were recruited on campus using standard procedures. The average age was 21 years for both females and males. Prior to being hired, subjects were screened for normal hearing and normal tympanometry using standard audiometric devices and procedures. Because of our interest in possible effects of the menstrual cycle on our measures, only females not using oral (or other hormonal) contraceptives were hired (called “naturally cycling” women). All subjects provided informed consent and completed an extensive questionnaire about previous noise exposure, drug use, and other topics. Some of the items provided information about sexual orientation. Nobody was excluded from the study because of sexual orientation, but 12 non-heterosexual subjects (7 females, 5 males) were excluded from the analyses reported here because of past findings ([McFadden and Pasanen, 1998, 1999](#)); their numbers were too small to justify any separate analyses.

Because race was not an anticipated variable, the only questionnaire items pertaining to race/ethnicity were the two required by our granting agency (reproduced in [McFadden et al., 2018](#), footnote 1). Those items, and our N 's, regrettably allowed only a partitioning of our subjects into two categories for data analysis—Non-White and White. As discussed in [McFadden et al. \(2018\)](#), we recognize the inadequacies of this race dichotomy, but it was the best we could do with the information available after the completion of the study. The questionnaires given to some of the early male subjects inadvertently omitted the two National Institutes of Health (NIH) items on race/ethnicity, and some additional subjects chose not to respond to those items, so those two groups were omitted from the analyses in which subjects are partitioned by race, but included when subjects are pooled across race; hence, the occasional discrepancy in the pooled and partitioned N 's.

The numbers of subjects contributing to the various comparisons are shown in the figures and tables. Those are the subjects remaining after we excluded those who did not complete the psychoacoustical testing and those who were not heterosexual. Also, for various technical reasons, not every subject contributed to every psychoacoustical and physiological measure, another reason the N 's vary slightly across comparisons.

B. Data collection

Subjects were hired as same-sex crews of 4–8 listeners. They participated in the psychoacoustical part of the study by working 2 h/day, 5 days/week, for several weeks. They were paid an hourly wage plus a bonus upon completion of all testing. Data were collected for seven psychoacoustical tasks: detection of a tone in the quiet, overshoot, bandwidth of the auditory filter, forward masking, tone-on-tone masking with a distortion product present (the Greenwood effect), detection of a tone with a complex and uncertain masker (profile analysis), and two-tone (lateral) suppression. The details of these tasks can be found in [McFadden et al. \(2018\)](#). Over the course of weeks of testing, tens of blocks of trials were collected for every psychoacoustical condition. After data collection was complete, the initial blocks of trials for every psychoacoustical condition were discarded as practice, any atypical blocks were discarded, and the four (for males) or six (for females) blocks most distant from each subject's own mean on that condition also were discarded. Thus, the subjects were highly trained on every task, and their data were culled to obtain the most representative blocks for averaging and for subsequent data analysis.

Male crews worked for 6–8 weeks. Sometime early in this period, the OAEs (and AEPs, reported elsewhere) of each subject were measured. Those individual test sessions typically were scheduled for times outside the 2-h daily window during which the psychoacoustical data were collected. Subjects stayed after their crew was finished, or came early, or worked out some other arrangement with the experimenters. For the males, OAEs (and AEPs) were measured in separate test sessions, each about 1.0–1.5 h in duration. OAEs (and AEPs) were measured in both ears in males—but only the right-ear data for OAEs are reported here.

Female subjects kept daily dairies on their menstrual cycles. After all the data were collected, this information was used to partition each individual subject's psychoacoustical data into three categories: menses, midluteal, and the remainder (nominally ovulatory). All partitioning was tied to the first day of menses. All blocks of trials collected during the first 5 days following menses onset were defined as menses, all blocks collected between 3 and 12 days prior to the onset of menses were defined as midluteal, and all remaining blocks were defined as ovulatory. Female crews worked for 8–10 weeks, meaning that for most subjects, at least some psychoacoustical data were collected for two occurrences of each of the three cycle phases, but because of weekends, holidays, and occasional absences, the number of blocks of trials collected during each cycle phase varied considerably.

Collecting the OAE (and AEP) data for the females was more complicated than for the males. In addition to keeping daily dairies, female subjects also kept the (all-female) experimenters orally informed about each onset of menses so that OAEs and AEPs could be measured during both the menses and midluteal phases. Because of our five-day definition of menses, the greatest urgency was associated with that phase of the cycle. Upon being notified of the onset of menses, the experimenters immediately scheduled an individual test session to measure that subject's OAEs and AEPs. If an

agreeable time could not be found outside the daily 2-h window during which the psychoacoustical data were collected, then OAEs and AEPs were measured during the crew time (while the rest of the crew was being tested on psychoacoustics). For females, both OAEs and AEPs were measured in a single session of 2.0–2.5 h duration. The total time was shorter than for males because OAEs and AEPs were measured only in the right ear for females (right ears exhibit more SOAEs and stronger CEOAEs than left ears—[McFadden and Pasanen, 1998, 1999](#)). Knowing the onset of menses for a subject, along with her self-reports of previous cycles, allowed the experimenters also to schedule another individual test session to measure OAEs and AEPs during the *predicted* midluteal phase. These test sessions typically were outside the daily 2-h window used for collecting the psychoacoustical data. Over the 8–10 weeks female crews were employed, there typically were multiple opportunities to measure OAEs and AEPs in each of the two menstrual phases for each subject. Accordingly, the OAE and AEP values used for analysis here were means across multiple measurement sessions, but different numbers across subjects and phases. The only subjects included in the analyses by menstrual cycle were those who supplied at least one usable OAE/AEP session during the menses phase and also at least one during the midluteal phase.

C. Voltmeter malfunction

After several all-male crews had been tested, the true root-mean-square (rms) voltmeter (VM) used for setting the levels of the stimuli for the psychoacoustical tasks malfunctioned. The malfunction was not discovered until the entire study was complete. Because of the malfunction, those early male crews were tested with stimuli that were 8.1 dB stronger than those used for the remainder of the male crews and for all of the female crews. Thus, the psychoacoustical data obtained from those initial 42 males could not be pooled with the data from the later crews, neither for the analyses reported in [McFadden et al. \(2018\)](#) nor for the correlations reported here. Instead we report the correlations separately for the males tested before and after the malfunction of the VM, called the pre-VMm and post-VMm males, respectively. (Again, because of the absence of race/ethnicity information, 12 pre-VMm males had to be omitted from some analyses reported here.) Also, comparison of any results involving the psychoacoustical tasks for the pre-VMm and post-VMm males is discouraged because of the differences in masker levels. Again, all the female crews were tested after the malfunction of the VM. Because the malfunctioning VM was not used in the measurement of OAE (or AEP) stimuli, pooling those data for pre- and post-VMm males was permissible.

D. OAEs

To measure OAEs, an Etymotic ER-10B+ microphone (Etymotic Research, Elk Grove, IL) was sealed snugly into the ear canal by fitting the microphone with an ear tip of appropriate size. For CEOAEs and DPOAEs, ER-2 earphones were used to produce the CEOAE clicks (one

earphone) or the DPOAE tones (two earphones). For SOAEs, only the microphone was used. The preamplifier output was led to a filter/line-driver combination that high-passed the waveform at 400 Hz (to eliminate low-frequency noise associated with gross bodily movements, etc.). The filtered output was passed out of the sound room to be digitized and stored on the disk of a Macintosh G4 computer (Apple Computer, Cupertino, CA). Analog/digital and digital/analog conversion and all digital control were accomplished using a digital interface board (model PCI-MIO-16XE-10; National Instruments, Austin, TX) resident in the Macintosh computer. The sampling rate for both input and output was 50 kHz with 16-bit resolution. Above 1.0 kHz, the noise floor of the system was about -17 to -23 dB sound-pressure level (SPL; 1-Hz bands, no time-averaging), sufficient to allow detection of quite weak OAEs. Collection and analysis of OAE (and psychoacoustical) data was controlled by LabVIEW® (National Instruments, Austin, TX) programs written by author E.G.P.

To measure OAEs, a subject was seated in a comfortable reclining chair inside an electrically shielded, sound-treated room having low illumination. The subject was allowed to relax alone for about 15 min prior to data collection, the goal being to avoid the initializing effects reported by Whitehead (1991) and McFadden and Pasanen (1994). The order in which the SOAE, CEOAE, and DPOAE data were collected was counterbalanced across subjects (and ears for the males).

SOAEs are essentially pure tones emitted from the cochlea. To measure SOAEs, we collected a digitized recording from the ear canal of 2–3 min duration in 30-s segments (sampling rate: 50 kHz). A recording duration of 2–3 min allowed for fairly strict off-line rejection of noisy time segments, with sufficient data remaining for spectral analysis. Dividing the recording into 30-s segments allowed the subject to be still and quiet for tolerably brief periods. These recordings later were analyzed for the presence of SOAEs using an objective algorithm (Pasanen and McFadden, 2000). Briefly, the least-noisy time segments were transformed into a power spectrum for each individual ear, that spectrum was smoothed, and only those peaks stronger than the local smoothed spectrum by a strict criterion were identified as potential SOAEs. Then, any smaller peaks within 0.1 octave of a large peak were discarded (see Zwicker, 1990). In accord with our standard practice, we identified SOAEs between 0.55 and 9.0 kHz for the analyses here.

CEOAEs are echo-like sounds emitted by the cochlea in response to brief sounds, such as the clicks used here. Clicks were presented at a nominal (but nonperiodic) rate of about 10/s, and the waveform from the ear canal was collected for 50 ms beginning with the onset of the click. The noise level in the ear canal was monitored continually, and clicks were not presented unless the noise level was below a predetermined value. The clicks were 100- μ s electrical pulses delivered to the ER-2 earphone, all at the same level and polarity (rarefaction). Immediately before CEOAE data collection in each ear, the click level was calibrated by a software routine that monitored the click amplitude in the ear canal and

adjusted the stimulus until a target click amplitude of 75 dB was reached. CEOAE data were collected for this click level. Then the click amplitude was reduced to 69 dB and the CEOAE was measured again (without recalibrating for the weaker click). To establish the target click amplitude for 75 dB, the following calibration was performed periodically: a 1.0-kHz tone of 75 dB SPL (re 20 micropascal) was displayed on an oscilloscope, and the level of the click was adjusted until its peak corresponded visually to the maximum amplitude of the tone. The click level required for that match was retained and used as the target for each OAE measurement session. To reflect this procedure, we designate the click levels for CEOAEs as decibels peak-equivalent SPL (dB peSPL).

The echoes obtained from 250 clicks were digitized (sampling rate: 50 kHz), summed, and saved to yield the averaged CEOAE waveform for that click level. Off-line, that averaged waveform was bandpass filtered between 1.0 and 5.0 kHz. Then, the rms amplitude of the filtered waveform was calculated over a 20.5-ms time period (1024 points) beginning 6 ms after the onset of the 50-ms waveform. That amplitude was converted to SPL in decibels (dB SPL) to obtain our measure of CEOAE strength. Because the recordings began at click onset, the click amplitude could be verified in every case; those rare recordings having aberrant or inconsistent click amplitudes were rejected from analysis. In accord with our standard procedure, we used the obtained waveforms themselves [no differencing (cf. Kemp *et al.*, 1986); both linear and nonlinear components included]. Because our clicks were weak, differencing was less important (Shera and Guinan, 1999). According to Guinan *et al.* (2003), our click levels should have produced only small efferent suppression effects.

When two tones of the appropriate frequencies are presented to the cochlea, the DPOAEs measured in the ear canal contain additional frequencies, called combination tones (CTs). The DPOAE of interest here was for the CT at the frequency $2f_{\text{lower}} - f_{\text{higher}}$. DPOAEs are known to fluctuate in magnitude when small frequency shifts are made in the pair of primary tones being used to evoke them (e.g., Martin *et al.*, 1998). Our standard procedure is to analyze DPOAE data in a way that averages over this microstructure (an exception was McFadden *et al.*, 2012). Specifically, for the DPOAE results reported here, six pairs of primary tones were used. All pairs had $f_{\text{higher}}/f_{\text{lower}}$ approximately equal to 1.21, and f_{higher} ranged from about 3.4 kHz to about 4.2 kHz. The frequency of f_{higher} increased in steps that were small-integer multiples of 48.8 Hz, and the $2f_{\text{lower}} - f_{\text{higher}}$ frequencies (the CT of interest here) varied from about 2.25 kHz to about 2.73 kHz. This selection of a common fundamental frequency permitted averaging of successive recording segments in the time domain, with consequent reduction in the noise floor. The primary tones always were equal in level.

Each pair of primary tones initially was presented at 50 dB SPL for 4 s and the strength of the DPOAE at $2f_{\text{lower}} - f_{\text{higher}}$ was measured. This was repeated as the level of the primary tones was decreased in steps of 7 dB until either the primaries were 36 dB SPL or the level of the DPOAE became -15 dB SPL or weaker (the noise floor for these

measurements was about -25 dB SPL). The primary tones then were set to 57 dB SPL, and they progressed to higher levels (in 7-dB steps) until either the maximum level of the primary tones was reached (71 dB SPL) or the DPOAE level obtained was within 3 dB of that obtained for the previous (weaker) pair of primary tones. This was done for each of the six pairs of primaries. For each 4-s sample, the 15% of time segments having the strongest amplitudes were discarded and the remainder used to obtain the strength of the DPOAE.

During analysis, the median DPOAE level across the six pairs of primary tones was calculated for each level of the primary tones for each subject. These median values were used to create a composite gain function, and a straight line was fitted to its linear range. The resulting fit was used to estimate the strength of the DPOAE when the primary tones were 50 dB SPL.

E. Analyses

The primary question of interest here is whether the individual differences in OAEs are associated with the individual differences seen in psychoacoustical performance. Accordingly, the primary comparisons of interest are the Pearson product-moment correlations between performance on the seven psychoacoustical tasks and the various measures of OAEs. Because of our psychoacoustical findings (McFadden *et al.*, 2018), also of interest is whether any of those correlations differ significantly by the sex, race, or menstrual phase of the subjects. Finally, another interest is the correlations between the various OAE measures themselves.

Because of the many variables of interest, a large number of correlations were calculated. In order to assess which outcomes were unlikely to be due to chance, a *resampling* technique was used. Specifically, correlations were calculated for all of the pairwise comparisons of interest; these are called the *actually obtained correlations*. Then, for each pair of conditions being compared, the obtained values for the first variable were retained for each subject, but all the values for the second measure were replaced at random by values achieved by other subjects in that same group. That correlation was calculated and saved (called a *resampled correlation*). The process of randomly reassigning the second value was repeated 20 000 times, and a tally was kept of how often the resampled correlation equaled or exceeded the actually obtained correlation for that comparison. That tally was divided by 20 000 to yield a proportion called the *implied significance* for the actually obtained correlation, an estimate of how rare the actual outcome was. When making our tallies we used the absolute value of the resampled correlations, meaning that our estimates of implied significance should be viewed as conservative (“two-tailed”). We have used versions of this resampling procedure in the past (e.g., *McFadden et al.*, 2012). *Cohen* (1992) suggested that correlations of 0.1, 0.3, and 0.5 be viewed as small, medium, and large, respectively. Here we use the term “negligible” to denote correlations that did not achieve implied significance values of 0.10 (marginally significant) or smaller.

III. RESULTS

The primary outcome was that OAEs and psychoacoustical performance generally were weakly correlated. For each type of OAE, we first present the basic results on sex, race, and menstrual-cycle differences; then, we present the correlations between that type of OAE and the various psychoacoustical tasks. Once those results have been reported for all three types of OAE, we present the correlations between the types of OAE themselves.

As noted above, the VM that malfunctioned was not used in the measurements of OAEs. Thus, it is legitimate to pool the OAE measurements collected from the post- and pre-VMm males, even though the psychoacoustical measurements cannot be so pooled. In the spirit of reporting all of the data collected, all of the figures shown here (Figs. 1–3) and Tables I and III show results for “post-VMm plus pre-VMm” males (or “Males, all”), sometimes along with post-VMm and pre-VMm males shown separately. The latter two categories are shown for comparison and consistency with the companion paper (McFadden *et al.*, 2018).

A. SOAEs

1. Sex and race differences

When the data were pooled across race, the average number of SOAEs in the right ear was greater for females

FIG. 1. Average number of SOAEs in the right ear for various groups of subjects over the range of 0.55–9.0 kHz. (Top) Subjects are pooled across race. (Bottom) Subjects are partitioned by race. For all figures shown here, the error bars denote the standard error of the mean, and discrepancies between the N 's for the pooled and partitioned conditions are attributable to absence of responses to the questionnaire items on race/ethnicity or to anomalies in the data collected for individual subjects. For comparison of the sexes, the left-most female and rightmost male bars are the most relevant in all the figures.

FIG. 2. Average root-mean-square (rms) amplitude of CEOAEs in the right ear for various groups of subjects, calculated over the range 1.0–5.0 kHz. Click level was 69 dB peSPL (peak-equivalent SPL); data obtained with a 75-dB click exhibited the same patterns. (Top) Subjects are pooled across race. (Bottom) Subjects are partitioned by race.

than for males (Fig. 1, top panel), in accord with numerous previous reports (e.g., Strickland *et al.*, 1985; Bilger *et al.*, 1990; Burns *et al.*, 1992; McFadden and Pasanen, 1999). The effect size for this sex difference was 0.73 (when the data were pooled over phase of the menstrual cycle and over all males), which was highly significant under resampling (see Table I, column 4). When the subjects were partitioned by race (Fig. 1, bottom panel), the sex difference diminished for Non-Whites but persisted for Whites. To our knowledge, this is the first report of race affecting the *sex* difference in SOAEs. Previous research had reported more SOAEs in Non-Whites than Whites (Russell, 1992; Whitehead *et al.*, 1993; McFadden and Loehlin, 1995), but our results confirm this only for the male subjects; for females, the race difference was slightly reversed. None of the race differences achieved implied significance (Table I, column 4). SOAE measurements obtained during menses and midluteal phases of the cycle did not differ.

When dealing with differences in differences, it is important to identify which condition(s) changed. Examination of the data in the bottom panel of Fig. 1 reveals that both sexes contributed to the larger sex difference for White subjects: the number of SOAEs was greater for White females than for Non-White females, and the number of SOAEs was smaller for White males than for Non-White males.

For comparison with the effect sizes shown here, effect sizes were calculated for the SOAE data collected by Russell (1992), who recruited “Euro-American” and “Afro-American”

FIG. 3. Average estimated magnitude of the DPOAEs produced at $2f_{\text{lower}} - f_{\text{higher}}$ by two primary tones each having a level of 50 dB SPL. Estimates based on composite gain functions created from combining six gain functions obtained using six pairs of primary tones having $2f_{\text{lower}} - f_{\text{higher}}$ values ranging from about 2.25 kHz to 2.73 kHz. (Top) Subjects are pooled across race. (Bottom) Subjects are partitioned by race.

twins. Those effect sizes for sex difference (female minus male) averaged about 1.0 calculated in different ways across zygosity and test ear; the sex differences for the monozygotic twins were larger than those for the dizygotic twins. The effect sizes for race difference (Afro-American minus Euro-American) averaged about 0.8 calculated in different ways across sex, zygosity, and test ear. [The effect sizes for ear difference (right minus left) averaged about 0.35.] Whitehead *et al.* (1993) did not provide sufficient information to calculate effect sizes.

2. Correlations with psychoacoustical tasks

The measure “number of SOAEs per ear” is inherently poor for comparisons involving correlations because of the relatively large number of ears having zero SOAEs. Here, zero SOAEs were found in the right ear for 7 of the 44 females measured during menses, for 4 of the 40 females measured during the midluteal phase, for 11 of the 27 post-VMm males, and for 12 of the 35 pre-VMm males. When these groups were partitioned by race, these proportions were somewhat higher for the Non-White females and somewhat lower for the Non-White males.

That said, the correlations between number of SOAEs in the right ear and psychoacoustical performance using that same ear are shown in Table II (columns 3 and 4 for females and males, respectively), both pooled and partitioned across race. For the females, the values used were pooled over the

TABLE I. Effect sizes for the comparisons shown for OAEs of different types, all in the right ear.

(1) Comparison	(2) Numerator for calculation	(3) Race	(4) Effect size		
			SOAEs ^a	CEOAEs ^b	DPOAEs ^c
Sex difference	Females ignoring cycle minus all males	Pooled	0.73^g	0.72^g	0.22
		Non-White	0.40	0.56^c	0.29
		White	1.20^f	0.91^c	0.24
	Menses minus all males	Pooled	0.51^c	0.73^g	0.17
		Non-White	0.15	0.58^c	0.29
		White	1.10^f	0.89^c	0.07
	Midluteal minus all males	Pooled	0.47^c	0.68^f	0.38
		Non-White	0.13	0.51^d	0.46^d
		White	0.91^c	0.87^c	0.40
Race difference	Non-White minus White	All females, ignoring cycle	−0.12	−0.24	0.04
		Menses females	−0.35	−0.24	0.20
		Midluteal females	−0.26	−0.23	0.02
		Males, post-VMm ^h	0.63	0.13	0.02
		Males, pre-VMm	0.30	0.07	−0.07
		Males, all	0.40	0.01	−0.04
Cycle difference	Menses minus midluteal	Pooled	0.01	0.12	−0.17
		Non-White	−0.07	0.15	−0.07
		White	0.15	0.06	−0.33

^aSOAEs = number of spontaneous otoacoustic emissions.^bCEOAEs = magnitude of click-evoked otoacoustic emissions.^cDPOAEs = estimated magnitude of distortion-product otoacoustic emissions for 50-dB primary tones.^dImplied significance, from resampling: $0.05 < p < 0.10$.^eImplied significance, from resampling: $0.01 < p < 0.05$.^fImplied significance, from resampling: $0.001 < p < 0.01$.^gImplied significance, from resampling: $0.0001 < p < 0.001$.^hVMm = malfunction of the voltmeter.

menstrual cycle. The vast majority of the correlations were small and did not achieve implied significance. None of the three correlations that did achieve marginal significance (flagged with superscripts) also did so for the opposite sex, making it unlikely that these outcomes would replicate.

Note that our resampling technique is considerably more conservative than the traditional method for determining the significance of correlations. For N 's of about 40 (our females pooled across race), correlations of about 0.30 and 0.39 achieve significance at the 5% and 1% levels of confidence, respectively, using the traditional method, and for N 's of about 25 (our post-VMm males pooled across race), correlations of about 0.38 and 0.49 do the same.

B. CEOAEs

1. Sex and race differences

CEOAEs were collected with two click levels, 69 and 75 dB peSPL. Because the patterns of results were highly similar, only the results for the 69-dB click are shown here.

Just as with SOAEs, when the CEOAE data were pooled across race, the average strength of the CEOAE was greater for females than for males (Fig. 2, top panel), in accord with previous reports (e.g., [McFadden and Pasanen, 1998](#); [Shahnaz, 2008](#)). The effect size for this sex difference was 0.72 (when the data were pooled over phase of the menstrual cycle and

over all males), which was highly significant under resampling (see Table I, column 5). When the subjects were partitioned by race (Fig. 2, bottom panel), the sex difference was notably larger for the Whites than for the Non-Whites. The effect sizes for race difference generally were smaller for CEOAEs than for SOAEs. CEOAE measurements obtained during menses and midluteal phases of the cycle did not differ.

In parallel with the results for SOAEs, both sexes contributed to the larger sex difference for White subjects: the strength of CEOAEs was greater for White females than for Non-White females and it was smaller for White males than for Non-White males.

Contrary outcomes have been reported. [Shahnaz \(2008\)](#) compared the CEOAEs of subjects from Chinese and Caucasian origins and reported that, like here, CEOAEs were weaker in the Caucasian group. Unlike here, the sex difference in CEOAE strength was the same for the two racial groups (effect size of 0.5 for their wideband measure). A possible explanation for this absence of an interaction between sex and race is that the Chinese group in the Shahnaz study might have been more homogeneous in pigmentation than was the Non-White group in our study. Other work suggests a possible involvement of the middle ear (ME; [Shahnaz and Davies, 2006](#)). Whatever the explanation, the results of both the Shahnaz and our studies do indicate that subject race—and by implication, degree of pigmentation—is strongly related to CEOAE strength.

TABLE II. Correlations of psychoacoustical task indicated with different types of OAE.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Psychoacoustical task	Race	Number of SOAEs		Magnitude of CEOAE		Estimated magnitude DPOAE for 50-dB primary tones	
		Females ^a pooled over cycle	Males ^b post-VMm ^c	Females pooled over cycle	Males post-VMm	Females pooled over cycle	Males post-VMm
Tonal detection in quiet (3.0-kHz tone, 300 ms duration)	Pooled	−0.04	−0.09	0.36	−0.29	−0.13	−0.21
	Non-White	0.04	−0.24	0.49	−0.42	−0.14	−0.12
	White	−0.31	0.07	0.13	−0.14	−0.12	−0.38
Overshoot (3.0-kHz tone, wide-band masker)	Pooled	0.05	0.09	−0.06	0.26	0.33	0.35
	Non-White	0.02	−0.02	−0.09	0.21	0.34	0.60
	White	0.17	0.28	0.09	0.34	0.31	0.01
Width of auditory filter (Equivalent rectangular bandwidth, ERB)	Pooled	−0.19	−0.13	0.23	−0.40^d	−0.05	−0.22
	Non-White	−0.10	−0.29	0.40	−0.48	0.11	−0.04
	White	−0.40	0.04	−0.06	−0.30	−0.34	−0.60^e
Forward masking (Tone on tone, 3.0-kHz, 42 dB SPL)	Pooled	0.05	0.41^e	−0.24	0.54^f	0.01	0.33
	Non-White	−0.18	0.42	−0.41	0.69^d	−0.04	0.39
	White	0.58^e	0.27	0.07	0.24	0.12	0.16
Greenwood task (Tone on tone, simultaneous + CT ^g masker)	Pooled	0.25	0.27	−0.17	0.21	0.04	0.36^d
	Non-White	0.27	0.29	−0.24	0.67^d	0.00	0.65^d
	White	0.17	0.20	−0.03	−0.26	0.13	−0.02
Profile analysis (3.0-kHz signal; 10-tone masker)	Pooled	−0.22	0.15	−0.05	0.17	0.30	0.12
	Non-White	−0.31	−0.07	−0.24	−0.03	0.13	0.13
	White	0.02	0.52^d	0.44	0.42	0.67^e	0.11
Two-tone suppression (3.0-kHz signal/masker; 3.45-kHz suppressor)	Pooled	0.01	−0.16	−0.15	−0.25	0.00	−0.37^d
	Non-White	−0.02	−0.35	−0.11	−0.38	0.11	−0.46
	White	0.11	0.11	−0.21	0.03	−0.18	−0.14

^aFemale *N*'s: Pooled 38–41, Non-White 25–28, White 12–13.^bPost-VMm male *N*'s: Pooled 24–27, Non-White 10–12, White 13–15.^cVMm = malfunction of the voltmeter.^dImplied significance, from resampling: $0.05 < p < 0.10$.^eImplied significance, from resampling: $0.01 < p < 0.05$.^fImplied significance, from resampling: $0.001 < p < 0.01$.^gCT = combination tone.

2. Correlations with psychoacoustical tasks

For comparisons involving correlations, CEOAE strength (and DPOAE strength) are superior measures to number of SOAEs because there are no zeros; essentially every subject provides a value for CEOAE (and DPOAE) strength.

The correlations between CEOAE strength in the right ear (with the 69-dB click) and psychoacoustical performance using that same ear are shown in Table II (columns 5 and 6), both pooled and partitioned across race. For the females, the values used for these correlations were pooled over the menstrual cycle. Most of the correlations were small, and the few that did achieve implied significance for the males did not for the females. The same pattern existed in correlations based on the 75-dB click. Apparently, having strong CEOAEs is not related to performance in the psychoacoustical tasks studied.

C. DPOAEs

1. Sex and race differences

As described above, gain functions for DPOAE magnitude were obtained for six pairs of primary tones, and a composite gain function was constructed from them as a way to

minimize the contribution from DPOAE microstructure. [The Greenwood results shown here differ in detail from those shown in [McFadden et al. \(2012\)](#) because there we used only the DPOAE data obtained from a single pair of primary frequencies (a single gain function).] Two reciprocal measures were extracted from the composite gain function—the estimate of the level of the DPOAE when the primary tones were equal to 50 dB SPL, and the estimate of the level of the primary tones necessary to produce a DPOAE equal to −5 dB SPL. These two estimates were extremely highly correlated (implied significance < 0.0001 for all groups), so only the analyses done on the estimated magnitude of the DPOAE produced by primary tones of 50 dB are reported here.

When the DPOAE data were pooled across race, the sex differences were in the same direction as those for SOAEs and CEOAEs (larger DPOAEs for females), but the differences (and effect sizes) were smaller (Fig. 3, top panel, and Table I, column 6). When the subjects were partitioned by race (Fig. 3, bottom panel), the sex differences were essentially the same, and small, for the two race groups (Table I, column 6). These small sex differences for DPOAEs replicate a previous report ([McFadden et al., 2009a](#)) where subjects were pooled across race. The race differences for

DPOAEs here also were smaller than those for SOAEs and CEOAEs. The magnitudes of the DPOAEs here were more than 50 dB below the level of the primary tones, and thus, similar to the results in some other species (reviewed in [McFadden et al., 2009b](#)). The relative size of the human DPOAE is even smaller when stronger primary tones are used (see [McFadden et al., 2009a](#)).

Early studies of DPOAEs asked whether the measured DPOAE was completely abolished when the *perceived* distortion product was canceled with a third tone ([Furst et al., 1988](#); [Zwicker and Harris, 1990](#)). It is not. That fact, plus a recent related study ([McFadden et al., 2012](#)) suggest that much of the DPOAE energy in the ear canal cannot be heard by its owner.

2. Correlations with psychoacoustical tasks

The correlations between psychoacoustical performance using the right ear and the estimated level of the DPOAE for primary tones of 50 dB SPL in that same ear are shown in Table II (columns 7 and 8), both pooled and partitioned across race. For the females, the values used for the correlations were pooled over menstrual cycle. Most of the correlations were small and did not achieve implied significance. The few correlations that did achieve implied significance did not also do so for the opposite sex, again making it unlikely that these outcomes would replicate.

D. Correlations between types of OAE

An obvious question is how similar the different types of OAE are to each other. Are some of them different manifestations of the same underlying processes? If so, those types of OAE ought to be highly correlated. Are some types of OAE manifestations of *different* underlying processes, as a widely accepted taxonomy of OAEs presumes ([Shera and](#)

[Guinan, 1999, 2003](#))? If so, those types of OAE should be less highly correlated.

The correlation matrix for the types of OAE measured here is shown in Table III. The correlations for the female groups are in the upper right of Table III (above the negative diagonal; in boldface) and those for the males in the bottom left (below the diagonal). The correlations are shown both pooled and partitioned across race, and the correlations achieving implied significance are flagged. For the females, these correlations were calculated using the values pooled across menstrual cycle. Here entries are shown for two click levels for the CEOAE even though the analyses for the higher-level click were omitted above.

The primary feature of the correlations in Table III is that the pattern of results is markedly different for males and females. For example, compare the first *column* of correlations (males) with the top *row* of correlations (females). The correlations between the number of SOAEs and the strength of the CEOAEs were universally larger for males than for females and many of the correlations for males achieved implied significance. A similar pattern is evident when the bottom row (males) is compared with the rightmost column (females); again, the correlations generally were larger for males than for females.

In addition, for females, there were no compelling differences by race, but for males, the race effects were less simple. When SOAEs and CEOAEs are compared (column 3), the Non-White males exhibited larger correlations than the White males, but when DPOAEs and CEOAEs were compared (bottom three rows), that pattern was not evident. We have no explanation for this complex pattern of results.

For no subject group were SOAEs and DPOAEs highly correlated, which is in accord with the argument that these two types of OAE have different underlying mechanisms ([Shera and Guinan, 1999, 2003](#)); also see [Wier et al. \(1988\)](#). Several investigators have reported correlations in the range

TABLE III. Correlations between the three types of OAE, shown separately for females^a (upper right, boldface) and all males^b (lower left).

(1) Type of OAE	(2) Race	(3) Number SOAEs	(4) CEOAE 75-dB click	(5) CEOAE 69-dB click	(6) DPOAE Magnitude
Number of SOAEs (0.55–9.0 kHz)	Pooled	—	0.20	0.28	0.30
	Non-White	—	0.16	0.27	0.29
	White	—	0.29	0.26	0.35
CEOAE magnitude with 75-dB click (1.0–5.0 kHz)	Pooled	0.42 ^c	—	0.93^f	0.10
	Non-White	0.48 ^d	—	0.91^e	–0.05
	White	0.19	—	0.96^f	0.35
CEOAE magnitude with 69-dB click (1.0–5.0 kHz)	Pooled	0.58 ^f	0.88 ^f	—	0.26
	Non-White	0.63 ^e	0.90 ^f	—	0.21
	White	0.49 ^d	0.84 ^f	—	0.38
DPOAE, estimated magnitude for 50-dB primary tones	Pooled	0.25 ^c	0.30 ^d	0.41 ^e	—
	Non-White	0.40 ^c	0.27	0.47 ^d	—
	White	0.02	0.54 ^d	0.46 ^c	—

^aFemale N's: Pooled 39–40, Non-White 26–28, White 12–13 (data pooled over menstrual cycle).

^bPost-VMm plus pre-VMm male N's: pooled 52–59, Non-White 27–31, White 18–20.

^cImplied significance, from resampling: $0.05 < p < 0.10$.

^dImplied significance, from resampling: $0.01 < p < 0.05$.

^eImplied significance, from resampling: $0.001 < p < 0.01$.

^fImplied significance, from resampling: $0.0001 < p < 0.001$.

0.5–0.7 between CEOAEs and DPOAEs (summarized in [McFadden et al., 2009a](#), p. 242).

For all groups in Table III, the correlations were quite high between the two CEOAE measures collected with different click levels (middle of the table). (For several of those comparisons, there were zero resamples for which the correlation exceeded the correlation actually obtained.) This (not unexpected) outcome can be taken as an indirect indication of high reliability in our measurements. These high values diminish the likelihood that the low correlations between OAEs and psychoacoustical tasks shown above are attributable to poor reliability of OAE measurement.

IV. SUMMARY AND DISCUSSION

A. Sex, menstrual-cycle, and race differences

To summarize the descriptive statistics for OAEs, when subjects were pooled across race, there were sex differences in both SOAEs and CEOAEs, but when the subjects were partitioned by race, the sex differences remained only for the White subjects, not for the Non-White subjects (Table I, columns 4–6, top). That is, there was an interaction between sex differences and race differences for SOAEs and CEOAEs. As expected, females had more SOAEs and stronger CEOAEs than did the males, in accord with numerous past reports ([Strickland et al., 1985](#); [Bilger et al., 1990](#); [Burns et al., 1992](#); [Russell, 1992](#); [McFadden and Pasanen, 1998, 1999](#)). In contrast, the sex differences for DPOAEs were smaller than those for SOAEs and CEOAEs (also see [McFadden et al., 2009a](#)), and there was no convincing evidence for an interaction with race. Said differently, for the subjects in this study, race differences appeared to be largest for SOAEs, smaller for CEOAEs, and smallest for DPOAEs. All differences across the menstrual cycle were negligible for all three types of OAE (Table I, columns 4–6, bottom). Understanding the mechanisms underlying these varying interactions between sex and race should be a goal for future research.

The correlations between the types of OAE differed by sex and by race (Table III), so few generalizations are possible. That said, SOAEs and DPOAEs were not highly correlated for any subject group, in accord with the taxonomy advanced by [Shera and Guinan \(1999, 2003\)](#). For Non-White males, the correlations between the number of SOAEs and CEOAE magnitude were large and statistically significant, and this contributed to those correlations being high and significant for the pooled males as well. By comparison, the correlations between SOAEs and CEOAEs were small for all of the female groups. We previously had reported a correlation of 0.76 between SOAEs and CEOAEs when the sexes were pooled ([McFadden and Pasanen, 1999](#)); those data were not analyzed by race.

The sex, race, and cycle differences in performance on the seven psychoacoustical tasks are detailed in a companion paper ([McFadden et al., 2018](#)). For six of the seven tasks, sex and race interacted, sometimes in ways that could obscure, or minimize, outcomes revealed when the data were pooled across race. It was those interactions that motivated the analyses by race reported here.

B. Correlations between OAEs and psychoacoustical performance

A primary goal of this study was to determine how performance on various common psychoacoustical tasks covaried with the OAEs measured on the same subjects. In general, the correlations between psychoacoustical performance and the various types of OAE were small. Although a few correlations did achieve implied significance under resampling (Table II), there was no consistency across sex or race. That is, for no pairing of psychoacoustical task and type of OAE was the correlation high for both sexes from the same race category (or for both races of the same sex). Thus, there was no compelling evidence that the mechanisms underlying OAEs contribute much to the psychoacoustical tasks studied here. This is a sobering outcome for those of us who long have thought about performance in various psychoacoustical tasks in terms of cochlear mechanics. A reasonable conclusion is that the individual differences that exist in psychoacoustical performance originate more in post-cochlear (neural) mechanisms than in the cochlear (“mechanical”) mechanisms that underlie the OAEs measured here. Note that the two psychoacoustical tasks showing the largest sex differences, the Greenwood and profile-analysis tasks ([McFadden et al., 2018](#)), exhibited similar patterns of (weak) correlations with the OAEs as the other psychoacoustical tasks.

The absence of strong correlations with OAEs is particularly surprising for detection in the quiet. OAEs long have been believed to be epiphenomena of the cochlear amplification performed by the outer hair cells ([Davis, 1983](#)), with strong amplification assumed to be associated with good hearing sensitivity. As one piece of early evidence, [McFadden and Mishra \(1993\)](#) showed that subjects having some SOAEs had better hearing sensitivity than subjects having no SOAEs, and that was true for both sexes, both ears, and all frequencies tested. The differences were 2–3 dB. However, those were group comparisons, not comparisons of individual subjects as the correlations reported here provide, and the latter do not support the idea of a tight relationship between OAEs and detection in the quiet for individual, normal-hearing subjects.

Cochlear amplification also has been linked to other psychoacoustical tasks studied here (that is why they were studied). Namely, overshoot is largest for low-to-moderate masker levels ([Bacon, 1990](#)). Also, hearing impairment of various sorts (reduction of cochlear amplification) can reduce overshoot ([Champlin and McFadden, 1989](#); [McFadden and Champlin, 1990](#); [Bacon and Takahashi, 1992](#); [Strickland and Krishnan, 2005](#)), reduce two-tone suppression ([Mills, 1982](#)), and increase the width of the auditory filter ([Tyler et al., 1984](#)). So the absence of strong correlations between individual differences in those tasks and individual differences in OAEs (and thus in cochlear amplification) also is somewhat surprising. A tentative conclusion is that having strong cochlear amplifiers, and thus, strong OAEs, may be related grossly to everyday hearing, but other, presumably neural, factors can modulate that relationship for individual listeners. The present data also

confirm that the relationship between DPOAEs and hearing sensitivity is weaker than initially expected, although different measurement procedures may reveal a stronger relationship (Martin *et al.*, 2016).

Some work has been done on relating OAEs to psycho-physical tasks other than simple hearing sensitivity (e.g., Probst and Harris, 1996; Neumann *et al.*, 1997; Smurzynski and Probst, 1999), but the subjects were largely unselected, the tasks were few, and the tasks did not cover a range of presumed dependency on the cochlear mechanisms responsible for OAEs. Walsh *et al.* (2010) compared an unusual type of OAE to performance in the overshoot task and observed numerous similarities between physiology and behavior, but also some subject differences that were difficult to explain.

The OAEs of certain special populations of subjects have been shown to differ from those of non-selected subjects (McFadden, 2011). The existence of only weak correlations between OAEs and psychoacoustical performance suggests that such special populations also are unlikely to differ in any of the aspects of everyday hearing tested by our psychoacoustical tasks.

C. Race is a proxy

Although two categories of race were used in this report, it is important to emphasize that the authors regard these categories to be a (poor) proxy for the difference that actually underlies the race effects reported here (McFadden *et al.*, 2018). We believe that the race differences noted here are attributable, partially or wholly, to differences in the activity of melanocytes in the individual cochleas of our subjects. Melanocytes are located at multiple sites in the cochlea, and there is evidence that the amount of melanin in these melanocytes covaries with the amount of melanin in the epidermis (discussed in McFadden *et al.*, 2018). People with darker skin have more SOAEs (Russell, 1992; Whitehead *et al.*, 1993; McFadden and Loehlin, 1995), better hearing sensitivity (although not in McFadden *et al.*, 2018), less noise-induced hearing loss, and less tinnitus than people with lighter skin (Agrawal *et al.*, 2008; Shargorodsky *et al.*, 2010; Lin *et al.*, 2012). Conversely, humans with albinism have more noise-induced hearing loss than people with darker skin (Garber *et al.*, 1982), and many drugs that are ototoxic bind to the cochlear melanocytes (Lindquist, 1973). Taken together, these facts suggest that somehow cochlear melanocytes are involved in the functioning of the cochlear-amplifier mechanism and in the protection of the cochlea from intense sounds (and/or in its recovery after such exposure).

While the commonly used categories of race are correlated with the individual differences in pigmentation, the correlation obviously is not high. There are wide variations in pigmentation within each category, and if our belief is correct, that variation is the source of much of the individual difference observed within race. As evidence of the weak correlation between race category and pigment-related characteristics, Lin *et al.* (2012) partitioned the subjects of a single race/ethnic category (Hispanic) into two groups based on individual skin color and found that the darker-skinned

subjects had significantly better hearing sensitivity than the lighter-skinned subjects. That is, the heterogeneity of the overall category was indeed simplified by further partitioning of the subjects by degree of pigmentation. Logic and intuition suggest that degree of pigmentation rightly should be viewed as a difference across individuals, not a difference across groups. Pigmentation and the auditory system has been discussed by McFadden and Wightman (1983), Lin *et al.* (2012), and McFadden *et al.* (2018), among others.

D. Possible errors

Might we have made some procedural errors that contributed to the generally weak correlations between OAEs and psychoacoustical task? Correlations can be reduced by manipulations that restrict the range of possible values. As explained in McFadden *et al.* (2018), we did exclude subjects not having “normal” hearing and we did cull atypical blocks of trials for individual subjects, but we do not believe either action was inappropriate. Indeed, had we not used normal-hearing listeners, some readers would have objected to this additional source of variability, and it would have affected the generalizability of our outcomes. Also, we believe that the culled blocks only contributed to a more accurate estimate of performance for each subject. Of course, we did study a highly select group: people who were college age, presumably middle class, generally healthy, normal hearing, etc., and study of a less select group might yield different results.

Measurements that are not reliable also can contribute to erroneous correlations. As noted above, the correlations here between CEOAEs obtained with two click levels were 0.84 and higher across subject groups (Table III). Correlations between certain psychoacoustical tasks also were reasonably high. The correlations between the two Greenwood conditions using different masker levels, and between the two profile-analysis conditions using different masker levels, were in the range of 0.75–0.95 across groups (McFadden *et al.*, 2018). Also, OAEs were measured multiple times for most of the female subjects and those measures were consistent, even with the potential confounding effect of the menstrual cycle. So reliability was good to excellent. Taken together, these facts argue against restriction of the range and poor reliability as errors of procedure here.

One might argue that our psychoacoustical tasks measured performance in relatively frequency-restricted regions (the vicinity of the signal), whereas the SOAEs and CEOAEs were broadband, global, measures, and perhaps that difference contributed to the weak correlations. Also, we intentionally used low-to-moderate SPLs for the behavioral tasks, and perhaps the correlations would be stronger if more intense stimuli were used. We respond “perhaps” to both suggestions, but we regard the experimental payoff of pursuing these factors to be slim. Logically, it is possible that if we had used different parameter values for some or all of the various psychoacoustical tasks, some of the correlations with OAEs might have been higher (as they were for the Greenwood task in McFadden *et al.*, 2012). But if higher correlations could be achieved only by judicious selection of

parameter values (for each subject separately?), the conclusion would be the same as it is now: global individual differences in OAEs seemingly have little relevance for individual differences in the broad spectrum of everyday hearing for normal-hearing listeners. That said, the matching of the acoustic stimuli in the behavioral task(s) with individual OAE microstructure might prove to be an interesting, if risky, manipulation for follow-up research.

One possibility is that the ME transfer function contributed to a lowering of the correlations between behavior and OAEs. For CEOAEs and DPOAEs, the eliciting stimuli pass through the ME on the path to the cochlea, and the OAEs travel back through the ME on the return path to the ear canal. By contrast, for the psychoacoustical measurements, only the initial pass through the ME is required. It is logically possible that differences in the inward and reverse paths and/or individual differences in the ME transfer functions modulated the individual differences in the OAE measurements and thereby reduced the correlations between OAEs and behavior. Because SOAEs also showed weak correlations with behavior, the implication is that the reverse path is the greater contributor to decorrelation if this ME explanation is relevant. To add (unneeded) complexity to this issue, note that [Shahnaz and Davies \(2006\)](#) have reported race differences in the ME characteristics of Chinese and Caucasian subjects.

E. Reproducibility

Reproducibility of results has become an active topic of discussion for some research disciplines ([Open Science Collaboration, 2015](#)). The present findings identify one subject variable (pigmentation, or less precisely, race/ethnicity) that has the potential to explain failures to replicate certain auditory findings. Investigators facing new data that do not align with outcomes from seemingly similar studies in previously published articles now need to consider that the reason for such discrepancies may simply be pigmentation differences across the subjects in the two studies. Two seemingly conflicting studies both may be correct; both may be highly reliable (replicable). The discrepancy may lie simply in the degree of pigmentation of the individual subjects tested. Most of modern auditory science is based on studies conducted during the latter half of the 20th century at major universities in the United States, Canada, and Western Europe. Accordingly, that science is based primarily on White subjects, because Whites were in the majority at those universities at that time. With the changing demographics in higher education, and with increased interest in audition at universities in other parts of the world, certain findings long believed to be true universally may prove to differ somewhat across Non-White groups. The current findings suggest that these differences will be subtle, but the reader must recall that the two race groups reported here were both highly heterogeneous internally. More precise sampling of subjects (using direct measures of individual pigmentation, not self-identified race) might reveal less subtle differences. Psychoacoustical studies commonly rely on small numbers of subjects measured repeatedly, making them especially

vulnerable to showing discrepancies with each other when the pigmentation characteristics of the subjects vary. Note that the pigmentation factor is less likely to be relevant for discrepancies between two older, published studies because the subjects were likely to be reasonably homogeneous (White) in older studies.

F. Final comments

In closing, we reiterate that the primary question for this study was whether the individual differences in OAEs covary with individual differences in performance on certain psychoacoustical tasks for normal-hearing listeners, with the hope that this knowledge eventually would lead to greater understanding of the mechanisms underlying both. The results obtained were not simple because of the interactions between sex and race, but the basic answer appears clear: individual differences in cochlear mechanics are not strongly tied to psychoacoustical performance. If this result is confirmed, it is informative about underlying mechanisms.

The present findings raise a number of questions about a number of topics, and ordinarily we would be planning additional studies to clarify various outcomes. However, this lab now is closed due to retirements, so we must leave the follow-ups to other investigators.

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